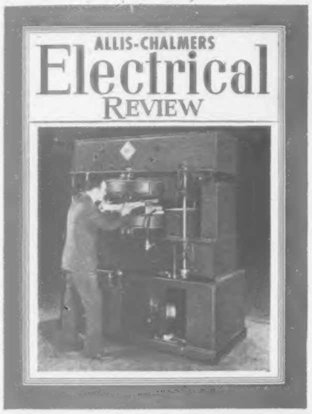
ALLIS-CHALMERS

Electrical REVIEW

S. R. Durand

Second and Third Quarter, 1946



20,000,000 VOLT TRANSFORMER with a one-turn secondary (front cover) expresses the basic principle of the new Betatron. In one minute of operation the Betatron produces X-ray radiation equivalent to that produced by a 100 milligram capsule of radium in six days. Other characteristics inherent in this development indicate great promise for its use in industrial, medical and scientific fields.

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Second and third quarterly issues have been combined in this publication. All subscriptions have been extended one issue.

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ALLIS-CHALMERS Electrical REVIEW

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ARC FURNACES of all sizes, from one-half ton to 100-ton capacity, are now equipped with Regulex rotating control, which eliminates contactors.

Regulex generators control electrode positioning motors on this 12-ton arc furnace by maintaining correct voltage on each arc at all times.

REGULEX—INSTABILITY IN HARNESS

T. B. MONTGOMERY
Engineer-in-Charge, Control Section
Allis-Chalmers Mfg. Co.

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A complete story of the Regulex rotating control at work — how it differs from standard direct-current generators.

TO the visitor, watching a huge rolling mill in operation for the first time, the sensation of such tremendous power under instant control is awe-inspiring. Red hot ingots lose their identity in a matter of seconds as they are rolled and re-rolled into plates weighing many tons.

In mills such as this, or in similar mills rolling aluminum bars from blooms, power for a city of 10,000 must at all times be under fingertip control. "Strike while the iron is hot" was never more important than in the fleeting minutes in a steel mill when an ingot remains near white heat.

Less spectacular to the casual eye but equally difficult in terms of the control required is the operation of tinning steel strip at high speed with a coat of tin less than 1/40th the thickness of a human hair. The tin must be electrically deposited on the strip smoothly and then remelted evenly to give a mirror-like finish over the entire surface. Current and speed must be controlled with extreme accuracy here, with an exact relation maintained between the two at all times.

Nerve center of the control for these two extremes in industry is the Regulex generator. Externally it looks much like other small d-c generators in essential details. Even with the armature removed, some of the similarity remains. The armature is wound essentially the same as other machines. It has laminated yokes and poles. It has more field windings than are found in a conventional d-c generator or exciter. One does not notice any other outstanding differences.

A design engineer would perhaps find the additional field windings unusual. Yet the Regulex generator is today doing hundreds of jobs like those mentioned in a way that no conventional generator can ever do.

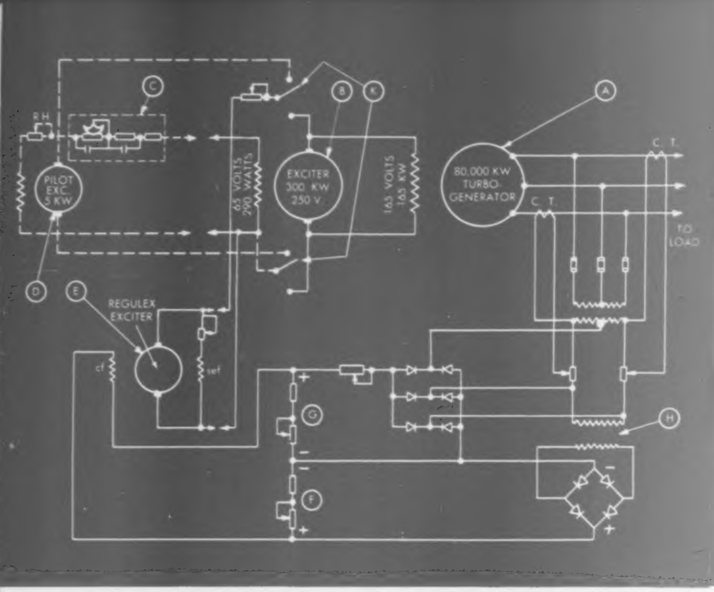
The few visible differences are actually the important ones. Many a layman, however, has found it difficult to understand the operation of a Regulex generator, perhaps because it is so simple and yet performs such a complex job. One of the best ways to explain Regulex control is to put it to work on a specific application and examine its operation in detail.

Regulex machine as a shunt generator

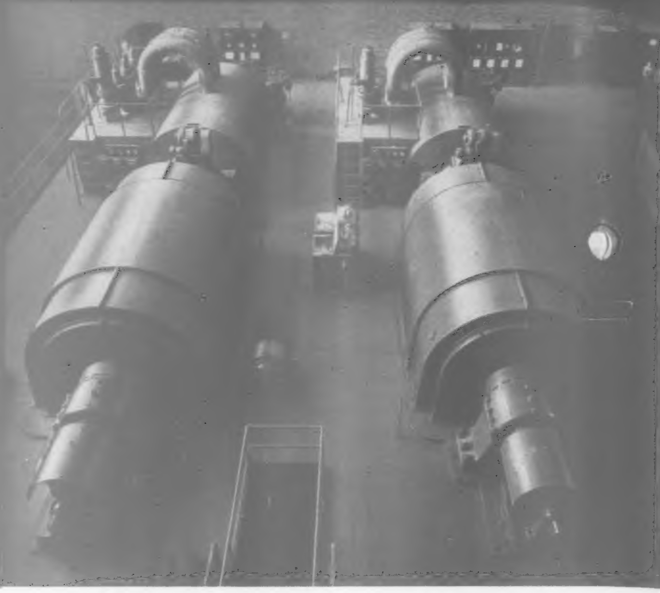
The Regulex generator in its more common applications is a shunt wound d-c generator supplying its own excitation from its output terminals. However, it has three important differences from a normal shunt generator. First, *the yoke contains more than twice as much steel as a generator of equal capacity and pole cross-section.* Second, there is, as mentioned earlier, at least *one extra field winding.* For simplification let us consider only one such extra control field present. Third, the self-excited field circuit is designed so that *inherently the proper excitation is supplied to maintain any value of power output.*

When a conventional self-excited shunt generator is started rotating, there is no voltage present at its terminals. Thus no excitation current is supplied to its field winding. The small amount of residual magnetism present is actually an excitation in excess of that corresponding to the delivered voltage. Therefore, voltage will appear at the brushes. This voltage causes current flow in the field winding, which causes the voltage to increase. The increase in voltage produces more flux to further increase voltage. This process would continue indefinitely were it not for saturation in the iron circuit which causes the flux in excess of that required to sustain the voltage to disappear.

In the Regulex generator, no building-up process occurs, except that due to the control or trigger field. The resistance



SIMPLIFIED DIAGRAM showing how a Regulex exciter can be adapted to provide instantaneous voltage control for an 80,000 kw turbo-generator. Commuters are only moving contacts in system. **(FIGURE 1)**



GENERATORS CAN BE PARALLELED and proper division of the load maintained by an initial adjustment of the current transformer circuits in Figure 1. Each generator then has individual Regulex control. **(FIG. 2)**

of the self-excited field circuit has been set so that the excitation required to sustain the output voltage is supplied by such terminal voltage at all values of output.

Normally the Regulex generator is used as an exciter for a larger generator. Some function of the larger generators' operation, such as speed, current, voltage or position, is translated into a voltage to be fed back to the "trigger" field in the Regulex exciter. It is important to bear this in mind—i.e. that *a Regulex generator is always used as an auxiliary device with its trigger field energized as some function of the output of the device under control.* This expresses one of the basic factors in Regulex operation. Let us now observe it at work.

Regulex controls a turbo-generator

In Figure 1, we have an 80,000 kw a-c alternator (A), with a field requiring 165 kw excitation input at rated load and voltage. To supply this excitation, a d-c generator (exciter B) is used which, in turn, requires 290 watts excitation input at 65 volts.

In generator design, it is customary for the control designer to take over beyond this point in the excitation circuit. He has, in the past, usually supplied a contact device for the circuit and a commutating device such as regulator (C) for regulating the flow of power input from a pilot exciter (D). One of the disadvantages inherent in this method of control is that the amount of power flow becomes dependent upon the mechanical operation of these devices, which when operated automatically must be motivated at power levels usually near the order of that required for metering. This results in relatively delicate and sensitive, constantly moving devices.

The variation in the power required to be handled by such devices is given in Figure 4, both in amperes and watts. To effect this variation resistance must be changed in the excitation circuit, and an additional loss, which may amount to a considerable percentage of the required excitation in many cases, is occasioned by the required external resistors. These resistors are shown in the circuits of mechanical regulator (C) at the top of the diagram.

Let us now substitute for this mechanical regulator a Regulex generator as shown at (E), Figure 1. This may enable us to gain a more complete picture of its characteristics and how it operates.

A typical Regulex generator required to furnish 290 watts at 65 volts would require 2 to 3 watts momentarily in the "trigger" field. The size of such a Regulex generator can be judged by comparison with the much larger 3 kw unit shown in Figure 3.

Referring again to Figure 1, the output voltage of the 80,000 kw generator is stepped down through conventional metering transformers and the average of the 3 phases is rectified and appears as a measure of output (G) across resistors 1 and 2. Opposed to this measure is the voltage of a constant voltage transformer (H), which is rectified and appears across resistors 3 and 4 as a standard of reference (F). In this circuit, so long as the generated voltage (G) is equal to the constant reference voltage (F), no current flows in control or trigger field, *cf*. When a difference between (G) and (F) exists, field *cf* is energized in one direction to lower the voltage (G) if it is too high, and in the opposite direction to raise the voltage (G) if it is too low.

Reliability is insured

An important point to note is that in this entire circuit there is no moving device to interrupt current nor to change its value by means of contacts or commutation devices, nor is any electronic device required. Output current is commutated by the brushes on the commutator of the high speed Regulex exciter, as with any d-c generator.

Therefore, the only moving parts in the system have the same reliability as the main exciter B on which the output of the 80,000 kw generator depends.

Characteristics are astatic

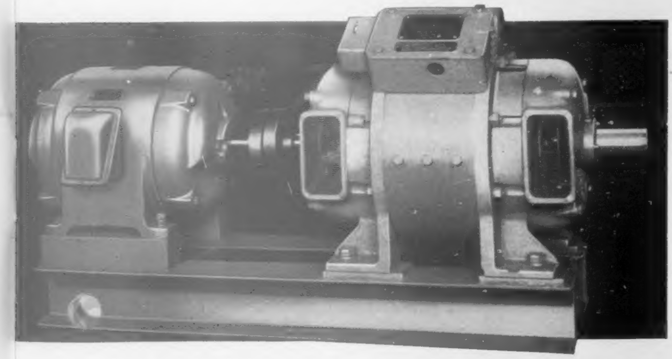
So long as control field *cf* is energized, with a given polarity, the Regulex generator terminal voltage will continue to change. In Figure 1 such energization is the result of a difference between voltage measure (G) and constant reference (F) and the system strives for equality between the measure (G) and reference (F). Thus it controls to zero current in control field *cf*. But from Figure 4, in going from zero voltage to ceiling voltage, a change in Regulex generator output from zero to 5700 watts is required with the same value remaining in control field *cf* after the change. To illustrate this, refer to Figure 1. Suppose that with normal generator voltage, and thus equilibrium between measure (G) and reference (F), there should be a sudden drop of 10 percent in generator voltage due to suddenly applied load. The resulting 10 percent difference between (F) and (G) would energize *cf* to raise generator voltage to restore it to normal. The restoration of voltage requires that the Regulex generator voltage increase somewhat more than 10 percent due to normal saturation in generator (A) and exciter (B). As this increase takes place, the current in control field *cf* is restored to zero when generator voltage reaches normal *but the Regulex generator remains at this higher voltage and watt output.*

This quality of changing values of Regulex generator output for the same value of control field input and, therefore, the same value of the quantity controlled is called "astatic."

It is brought about in the Regulex generator by the fact that the self-excited field *sef* in Figure 1 supplies all of the excitation required to sustain any voltage output but no more or less than is required for this voltage output. A change in voltage then must be effected by energization of control field *cf*.

Self-excitation — how it is accomplished

Perhaps we can best see further how this is accomplished by returning again to the question, "How does the Regulex differ from the conventional d-c generator?" To illustrate the difference, it will be necessary to resort to a few terms used by the designer of d-c machines. Normally a designer lays out his machine for maximum efficiency and good stability. For the purpose of this discussion, main exciter (B) in Figure 1 is a conventional d-c generator. The Regulex generator is a self-excited d-c machine. Suppose that exciter (B) be disconnected from both the Regulex generator (E) and the regulator (C) and that double pole knife switch (K) be closed in the up position connecting its shunt field to the terminals of pilot exciter (D). The relation in this field circuit, between volts, as supplied from pilot exciter (D), and ampere turns in the field is given by line OF in Figure 5, if the combined resistance of the field and rheostat RH is 29.4 ohms. It is obvious that this must be a straight line because from ohms law if the voltage is doubled the field current is doubled and since the turns on the poles of the field remain constant the ampere turns are doubled. The ampere turns are a measure of the excitation (mmf producing flux) of the machine.



REGULEX GENERATOR rated 3 kw is at right. Unit shown is larger than equivalent rating d-c generator to allow quick response and accurate control. Adjusted at installation, units require little maintenance. **(FIG. 3)**

Suppose now that the resistance of rheostat RH, Figure 1, is decreased so that the field circuit resistance is 14.7 ohms instead of 29.4 ohms as before, or just one-half as much. The new relation between volts and amperes is given by line OF', and, since the resistance has been reduced to one-half, twice as many ampere turns are produced for the same voltage V-V'. This line OF or OF' is called the *field resistance line* and gives the *ampere turns excitation per volt* applied to the field circuit.

By reducing resistance this line is rotated clockwise around the origin O, or by increasing resistance it is rotated counterclockwise. With infinite resistance the line will move to the left to coincide with the vertical axis.

However, this rotation of the field resistance line may also be accomplished by changing the number of turns of the field winding with the same resistance in the circuit or *by changing both amperes and turns. This is a point to remember in considering the Regulex generator.* In Figure 5, the resistance line passes through the origin O because the machine is self-excited and excitation becomes zero when output voltage is zero. When the field is separately excited this line does not necessarily pass through zero as will be shown.

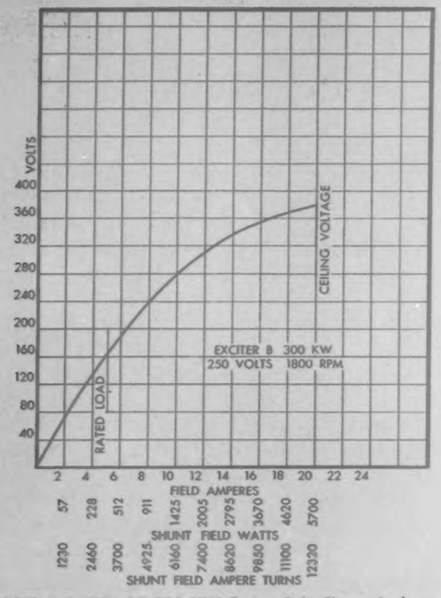
In Figure 4, which is the saturation curve of exciter (B), ampere turn excitation values are shown on the horizontal axis. This curve gives the *volts delivered at the brushes for all values of total ampere turn excitation.*

Suppose then that rheostat RH of Figure 1 is set to give resistance line OF in Figure 5 and that 250 volts are delivered by pilot exciter (D). Then 5244 ampere turns will be produced in the field from Figure 5. From Figure 4 this results in 250 volts being produced in exciter (B). The same voltage is applied to the main generator field circuit as is produced at the terminals of exciter (B).

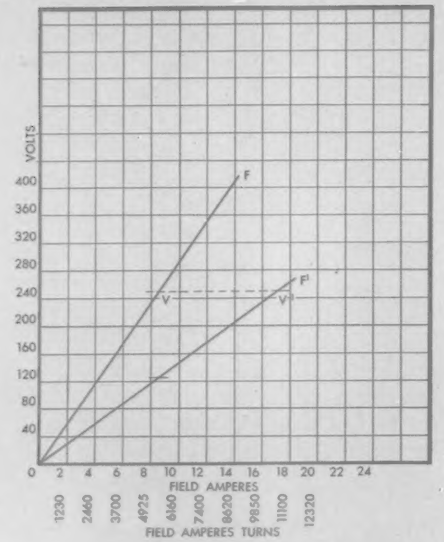
Suppose then that knife switch (K) be thrown down (without opening the circuit). The excitation will not change and the voltage will not change. The exciter is now supplying its own excitation in the correct amount.

We now can combine the saturation curve and resistance line. Since the voltage for excitation is taken from the terminals of the machine, the combined curves are as shown in Figure 6 and the machine operates at voltage N, as pointed out earlier. It cannot operate at any other voltage without change in the resistance of the field circuit.

The machine is then said to be stable because voltage will be held definitely at point N since at this point there is an angle between the field resistance line and saturation curve. The larger this angle the more stable the machine becomes. Thus, at point N' the machine is more stable than at point N on the curve because this angle is larger. Line OF' corresponds to the field resistance line with a minimum of field resistance in the circuit.



SATURATION CURVE OF 300 KW Exciter B in Figure 1 shows relationship between field amperes, watts and ampere turns. **(FIGURE 4)**



FIELD RESISTANCE LINES for Exciter B in Figure 1 are shown at different field rheostat positions. Higher resistance is at left. **(FIGURE 5)**

A bending saturation curve then is required for *stability.* This form of curve is also required for most *efficient* use of materials because, as more and more flux is crowded through iron, less and less flux is produced per ampere turn increase. In order to get the most flux in a given pole, saturation results.

Instability created

We have considered a standard d-c shunt generator. Suppose now that in Figure 6 the resistance of the field circuit be increased until the resistance line is rotated counterclockwise to OF" where it is coincident with the straight portion of the saturation curve. Here the machine is very unstable, because with a momentary shift in voltage the ampere turns supplied will become too small or too great, and voltage will shift violently up or down over wide limits. In fact, it will shift between the limits from point P positive on the saturation curve to point P' of equal value negative on the slightest change in voltage due to any disturbance. Voltage cannot go above P nor below P' since beyond these points the saturation curve and resistance line separate, resulting in insufficient ampere turns to support further change. *This type of instability is precisely what is required in a good regulating device,* whereas it cannot be tolerated in a normal machine.

However, under conditions of steady voltage at any value between points P and P' the shunt field supplies just the correct amount of excitation to maintain that voltage as it did at point N, Figure 6. This illustrates the third essential difference between a conventional d-c generator and the Regulex generator.

Let us now build such a generator, one in which the field resistance line overlaps the saturation curve in order to provide maximum instability. This is a start in the design of the Regulex generator. If we build into the stator of the generator an additional shunt field suitable for connection into the controlled circuit, we have a Regulex generator in its simplest form, complete with both shunt and control fields.

The resulting saturation curve (Figure 7) for the Regulex exciter shown in Figure 1 is straight over the normal operating range and the resistance line OF is made coincident with it.

Thus no excitation is required at any given normal operating voltage other than that delivered by field *sef* in Figure 1.

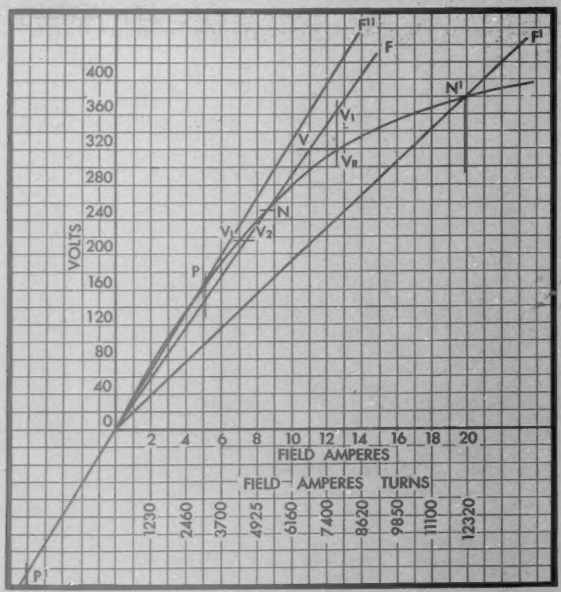
Stabilization by control

Let us analyze how the control field of Figure 1 commands the actions of the turbo generator.

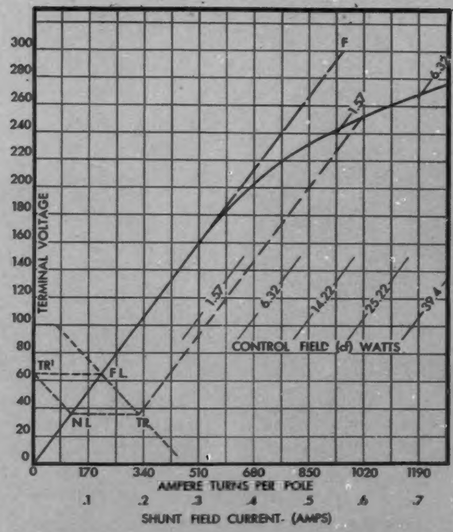
Suppose the system of Figure 1 is operating at no load and normal voltage. This condition requires 37 volts on the Regulex generator and 85 volts on exciter (B). Under this condition there is no current in control field *cf* of Figure 1 and the self-excited shunt field *sef* has approximately 4.1 watts supplied to it from the terminals of the Regulex generator which produces 115 ampere turns.

If full load at 80 percent power factor is suddenly applied to generator (A), a sudden drop in voltage will occur, due in principal part, for the purpose of this discussion, to insufficient excitation to carry the load. Assume that instantaneously the voltage at the terminals of generator (A) drops 15 to 20 percent. This reduces the voltage of measure (G) by 15 to 20 percent, but reference (F) remains at its constant value. The difference between (G) and (F) will energize control field *cf*. Circuit components have been chosen so that this difference of 15 to 20 percent energizes control field *cf* to the extent of 2.37 watt. This adds 208 ampere turns excitation to the field and the new excitation is shown by line NL-TR, Figure 7. The total excitation now is 323 ampere turns (shunt field plus control field). The voltage of the Regulex generator will immediately increase, increasing the voltage of exciter (B) and in turn generator (A).

To return the voltage of generator (A) to normal requires that the voltage of exciter (B) increase to 165 volts. This requires that the Regulex generator voltage increase to 65 volts under steady state conditions. However, as the voltage of generator (A) returns to normal the difference between (F) and (G) is reduced proportionately and disappears when normal voltage is reached. The variation in energization of



SATURATION CURVE AND FIELD RESISTANCE LINES for Exciter B in Figure 1 are combined. Voltage is reversed at P'. **(FIGURE 6)**



CHARACTERISTIC CURVES FOR REGULEX Exciter in Figure 1 at various control field excitation values are shown above. **(FIGURE 7)**

control field *cf* under this condition is represented by line TR-FL. At FL all excitation (204 ampere turns, 3 watts) is again supplied by the self-excited field *sef* and there is zero current in the control field *cf*. The watts in the self-excited field are not important because this energy is supplied from the Regulex generator output. The power required in the control field must be kept low, however, to maintain high sensitivity.

Line TR-FL is the *apparent field resistance line.* It will be noted that it does not pass through zero since control field *cf* is supplied from a separate power source. As previously explained, the Regulex field resistance line was shifted initially to coincide with the straight line saturation curve by means of change in resistance of the field circuit. However, it was also stated that this curve can be changed by change in ampere turns of total excitation. Thus upon the sudden application of full load on the generator (A), the resulting ampere turns due to energization of control field *cf* causes the resultant field resistance line to revolve about point FL, which is the new value of Regulex terminal voltage required for correct full load voltage at generator (A). The apparent resistance line, which appears only during changes, does not pass through zero. It intersects the saturation curve at a large angle showing inherent stability of the system. Such stability means that the Regulex generator and, in turn, the entire system, will be held at a definite voltage under steady state conditions. By this means, the system, which was made unstable by the characteristics built into the Regulex generator, is stabilized by the control means used for regulation.

When main generator voltage rises due to a sudden load drop or other disturbance, control field *cf* is energized in a direction opposing that of the shunt field. As a result total effective ampere turns are reduced and generator voltage drops to the correct value immediately.

In this application the value of control field *cf* energization is large compared to the value of self-excited *sef,* Figure 1. It is evident that the larger the ratio of the values of these fields, the faster the response will be.

Wide range of design possible

The conditions chosen of a sudden application of full load would not be met in service except in case of line fault on the system. Under these conditions, high speed response is essential to system stability.

At normal steady state conditions, theoretically no current flows in the control field *cf*. Actually a minute current is constantly flowing to overcome inaccuracies in the amplifier system. Theoretically the amplification factor is infinite. In practice it has a high value but does not approach infinity. The exciter shown in Figure 1 has an amplification factor of $\frac{3000}{0.2}$ or 15,000. In Figure 2 the overall system amplification is $\frac{80{,}000{,}000}{0.2}$ or 400,000,000. Such values sometimes occur in Regulex control. The important thing is that the control power is 2 to 3 watts, a value well within the range of metering circuits.

Many industrial applications do not require such high speed response, nor is it desirable. A ratio of 60 percent = $\frac{\text{control field}}{\text{self-excited field}}$ is often used. This value is normal for Regulex exciters used as field supply for typical steel mill operations mentioned earlier. Maximum acceleration and deceleration of the main mill motors, either forward or reverse, is automatically assured without excessive load current at any time.

Some such applications utilize both series and shunt type of self-energized fields. When two or more variable functions must be translated into the correct electrical action, additional control fields are used in the same generators.

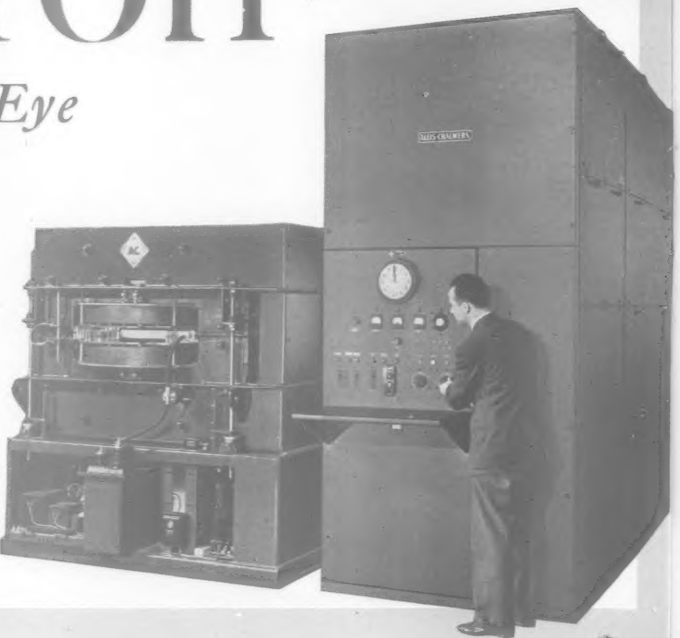
Although Regulex control has been in use in the iron and steel industry for several years, hundreds of possible applications throughout all industry have yet to be explored! With Regulex rotating control the way has been opened to a new field in automatic control design to do the job quicker, safer, and more economically than ever before.

Betatron—

Industry's New Seeing-Eye

J. P. GIRARD
Transformer Section
Allis-Chalmers Mfg. Co.

The Betatron, by virtue of its present industrial uses, may well prove to be the greatest step in X-ray development since Röntgen's original discovery.



BETATRON AND CONTROL UNIT shown awaiting shipment. In use, units are normally separated by shielding wall on three sides of Betatron. (FIG. 1)

SINCE the discovery of X-rays by Röntgen in 1895, scientists and engineers have been constantly striving to produce X-rays of higher energy. It is this radiation having greater energy or shorter wave length which produces more penetrating X-rays. With the development of the resonance transformer X-ray machine a few years ago we seemed to have reached the practical limit for acceleration of electrons by the application of the potential directly across the tube at about the two million volt point.

However, with the development of the betatron, which accelerates electrons by magnetic induction, it has been possible to extend the X-ray energy values from two million electron volts up to hundreds of millions of electron volts.

The development of the betatron with the final contribution by Kerst and Serber which resulted in the first workable machine was the result of the contributions of many scientists over a period of years. The basic idea of accelerating electrons by magnetic induction was patented by J. Slepian in 1927, which is the earliest published work by anyone. Walton, Wideroe, and Steenbeck developed equations giving the necessary field conditions for an electron accelerator, but were not able to produce a machine which would work. Kerst and Serber developed the equation for the transient phenomenum of the electrons traveling in a magnetic field and placed a source of electrons together with a means of giving them an initial velocity by the application of a pulse of voltage in the magnetic field near the orbit. From their calculations Kerst constructed the first successful betatron at the University of Illinois.

Since a charged particle moving in a magnetic field travels in a curve, it is possible to have a field in which an electron will travel in a given circle. By constructing the field so that the flux within this circle or equilibrium orbit is equal to twice the area of the equilibrium orbit times the field at the orbit, and the field in the region of the orbit to be proportional to $1/r^n$ where n is between zero and one, the electrons will remain in this orbit when it is accelerated by a field.

Transformer secondary is electron stream

In the operation of the betatron, electrons are injected from an electron gun or injector while the field is small. The injector is situated in the magnetic field slightly outside the orbit. The electrons are given a velocity corresponding to the field at the time of injection and are focused by the field to the equilibrium orbit so that they miss the injector on succeeding revolutions. The increasing field produces an energy increase equal to that which would be produced by a voltage that might be measured across a single turn coil at the orbit. Speed of the electron stream increases with each succeeding revolution until the electron mass increases relativistically to approximately 40 times[1] that of the rest mass. Final speed approaches 99.97 percent that of light.

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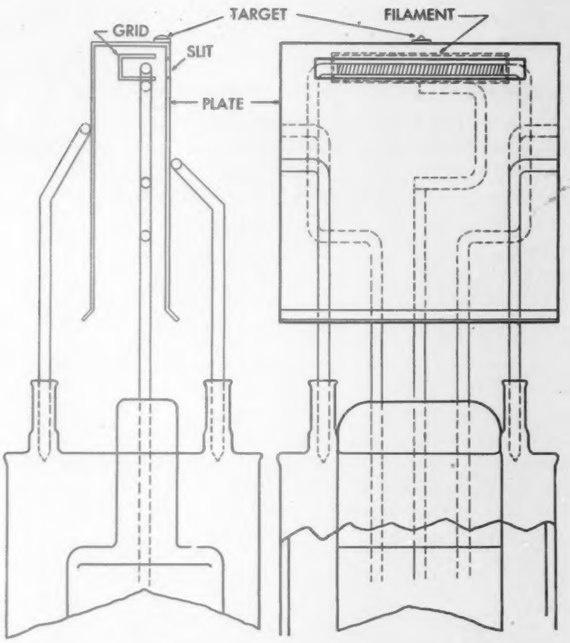
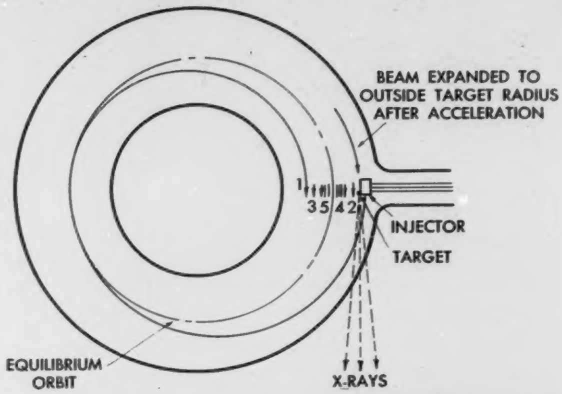
1. From the Einstein Relativity Formula—

$$\text{Mass at Velocity } v = \frac{\text{Mass at rest}}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

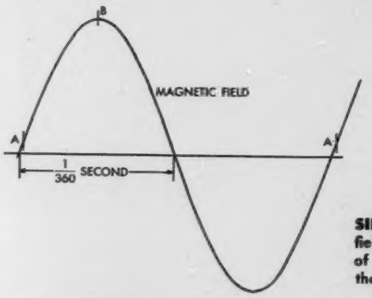
where c = speed of light = 3×10^{10} cm sec.



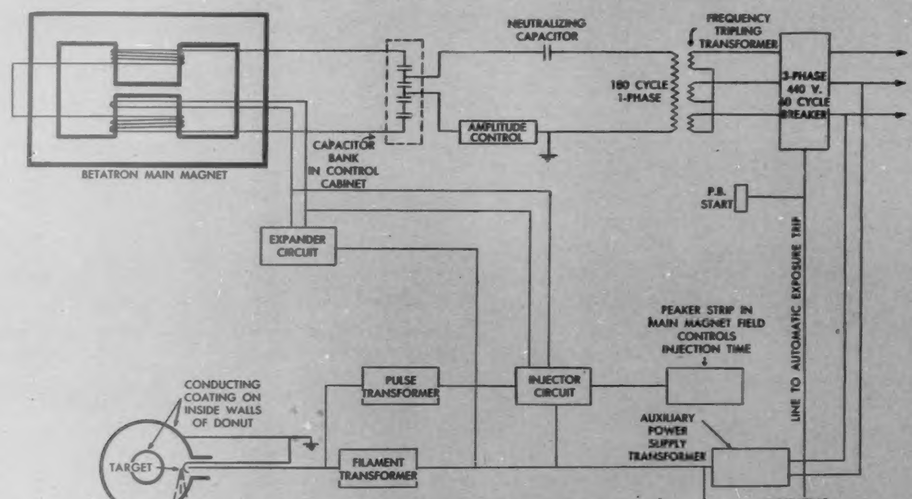
FILAMENT, PLATE, GRID AND TARGET STRUCTURE are illustrated in side and end views. The target, normally of platinum or tungsten, is a pin-point source of high energy X-rays. **(FIGURE 2)**



VIEW THRU DONUT looking down shows how successive electron paths approach equilibrium orbit near donut center. **(FIGURE 3)**



SINE WAVE of magnetic field strength showing time of injecting and diverting of the beam. **(FIGURE 4)**



ESSENTIAL ELEMENTS of automatically controlled Betatron are shown above. The ionization chamber (lower left) measures X-ray density. The integrating monitor circuit (lower right) trips magnet breaker when predetermined X-ray value is reached. **(FIGURE 5)**

As the electrons are traveling in a vacuum, they make many revolutions while the flux linking the orbit is increasing, their final energy becoming approximately that which would be generated in a coil having the same number of turns as the revolutions made by the electrons. Thus, the design of betatron makes possible accleration of electrons to very high energies with low voltage equipment. For instance, in the 20 million volt betatron the electrons are given the same energy they would receive in being accelerated by a potential difference of 20 million volts, while the voltage required to create the necessary field for their acceleration by magnetic induction is about 100 rms volts per turn on the magnet coil.

In the operation of the betatron, the simplest method of producing a time-varying flux is by the application of a sinusoidal voltage to the coils which effects a sinusoidal magnetic field as shown in Figure 4. The electrons are injected at point A, shortly after the field has passed through zero. Acceleration takes place as the field increases until it reaches its maximum value, point B, at which time the electrons are caused to deviate from their orbit and strike a target, producing X-rays.

CONTROL CUBICLE with sides removed and control panel swung open. Main power transformer is in separate compartment. **(FIGURE 6)**

In the 20 million volt machine the electron stream is diverted by a pulse of current flowing through a turn of wire fastened to each pole face slightly inside the equilibrium orbit. When diverted the electrons spiral outward until they strike the target mounted on the back of the injector. The relative position of the injector, target and equilibrium orbit in the evacuated annular chamber, called the donut, are shown in Figure 3.

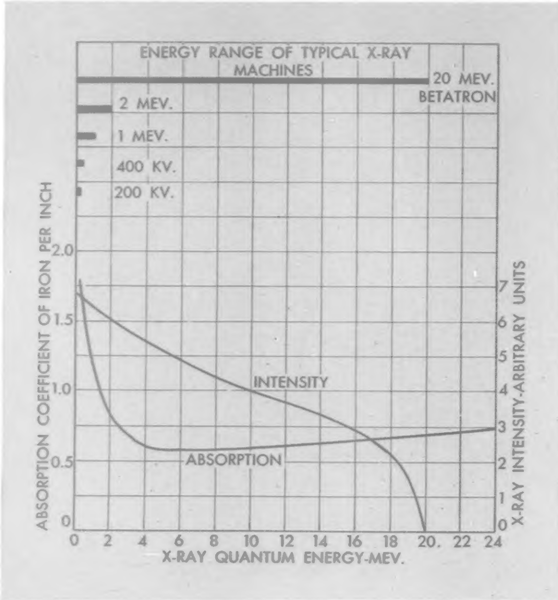
When electrons are slowed down or stopped by the target, part of the energy is transformed into X-rays. Since this conversion becomes more efficient at higher energies (about 65 percent at 20 million volts compared to 1 or 2 percent at one million volts) the X-ray yield of the betatron is large enough to be usable even though the current in the tube is less than one microampere. The electrons in spiraling out from the equilibrium orbit make successive revolutions with a change in radius of the order of 10^{-4} centimenter per revolution. This means that they strike only the very tip of the target, resulting in thin target radiation, with very little of the radiation being filtered in passing through the target.

Radiations have ideal characteristics

Twenty million volt X-rays exhibit certain characteristics not found in lower voltage rays which make them particularly applicable to thick section radiography. Some of the characteristics of the 20 million volt X-rays are as follows:

Maximum penetration: Experiments have shown that rays near the 20 mev point have ideal characteristics for radiographic work on heavy steel sections from the standpoint of maximum penetration without loss of detail. This characteristic also holds true for brass, bronze and copper.

Low radiographic figure of merit: The radiographic figure of merit is the ratio of the total exposure on a film to the exposure due to primary X-rays only. Since secondary and higher order X-rays which are produced in the process of the absorption of the primary X-rays travel at some angle with the primaries, they tend to reduce the detail of a radiograph. For 20 mev radiation the radiographic figure of merit is about 1.2. This can be compared to a value of 1.7 at 10 mev and approximately 10 at 1 or 2 mev.



ABSORPTION CURVE for steel and theoretical X-ray spectrum showing radiation for various energy values of 20 mev betatron. **(FIGURE 7)**

Absolute sensitivity: With lower voltage X-rays the size of the minimum flaw which can be detected varies with the thickness being radiographed and the position of the flaw in the specimen. Twenty mev radiographs exhibit absolute sensitivity. The minimum detectable flaw is the same for any thickness of specimen or the position of the flaw in the specimen. For instance, a flaw of 1/32 of an inch is detectable in steel in thicknesses from 2 to 12 inches using Eastman Type A film.

Latitude: The variation in thickness of a given specimen which it is possible to examine on one radiograph is referred to as latitude. This means that it is practical to make radio-

graphs of specimens having a great difference in thickness on one film without building up the thinner sections, a time-wasting procedure.

No blocking required: As a result of the load intensity and small diversions of the secondary radiation no blocking is required around the outline of an irregular section in radiography with 20 mev radiation. In contrast to this, it is often necessary to block around the outline of irregular specimens in lower voltage radiography with considerable loss of production time.

Size of X-ray beam: The maximum intensity of 20 mev X-rays is in the direction of the electron stream at the time it strikes the target. This intensity falls off 50 percent at 4½ degrees from the center, and somewhat more gradually at larger angles. This fact makes the protection of personnel from the radiation much easier.

Small focal spot: This characteristic is a betatron feature and is not obtainable with any other X-ray machine. The natural focal spot size of the betatron is 0.050 inch high by less than 0.005 inch wide. By use of a special target the height can be reduced to 0.010 inch.

War promoted betatron development

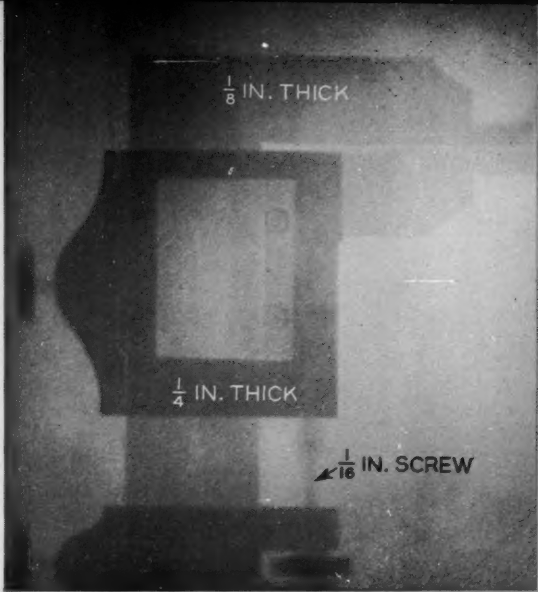
After Dr. Kerst had developed the first successful betatron, he designed and supervised the construction of a 20 million volt betatron which was permanently loaned to the University of Illinois. He was then authorized by the Office of Scientific Research and Development to study the properties of X-rays up to 20 mev to determine whether or not they would be suitable for use in the war effort. In this investigation the X-rays were found to have the characteristics outlined above and authorization was given to proceed with the development of a machine suitable for industrial use in thick section radiography. For this development he enlisted manufacturing aid and, subsequently, the first commercial betatrons were constructed for a number of Government arsenals.

The use of the betatron in thick section radiography will make possible the same refinements and improvements in the design of heavy metal sections as has been possible in thin sections. The advantages can be visualized in the radiographing of assemblies to determine whether or not parts are properly aligned and if the tolerances are correct. The elimination of the necessity for building up thin sections and blocking around irregular objects will greatly simplify the making of radiographs when using the betatron.

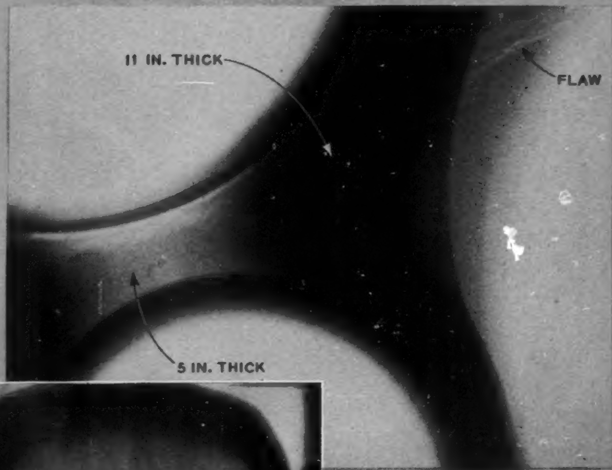
In the fields of both nuclear research and medical therapy, the betatron holds much promise. It offers a convenient, easily controlled source of high energy radiation necessary in the study of nuclear reactions. Along with the cyclotron and the new synchrotron it promises to become one of the standard tools of atomic physicists.

Perhaps the most appealing of all its possibilities lies in the betatron's use in medical therapy. Only a small bit of the vast amount of research, that must be done before the betatron can be fully utilized in the treatment of cancerous growths, has as yet been done, but tests up to the present time have been encouraging.

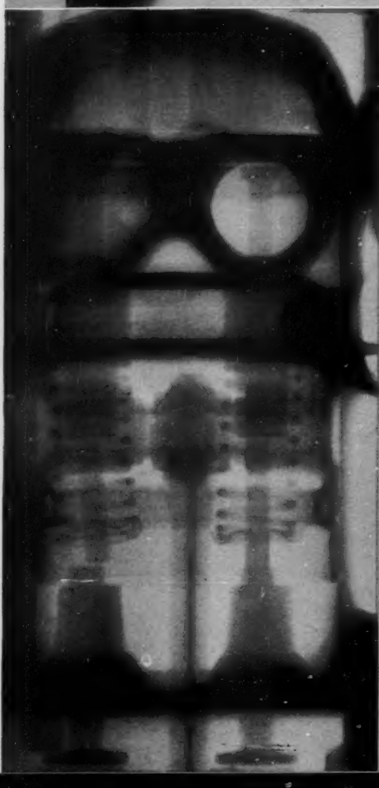
Recently the electron stream itself has been brought out through the walls of the donut, providing a new instrument for medical research. With such a promising future as well as a very useful present, the betatron presages to become one of science's most useful tools in the very near future.



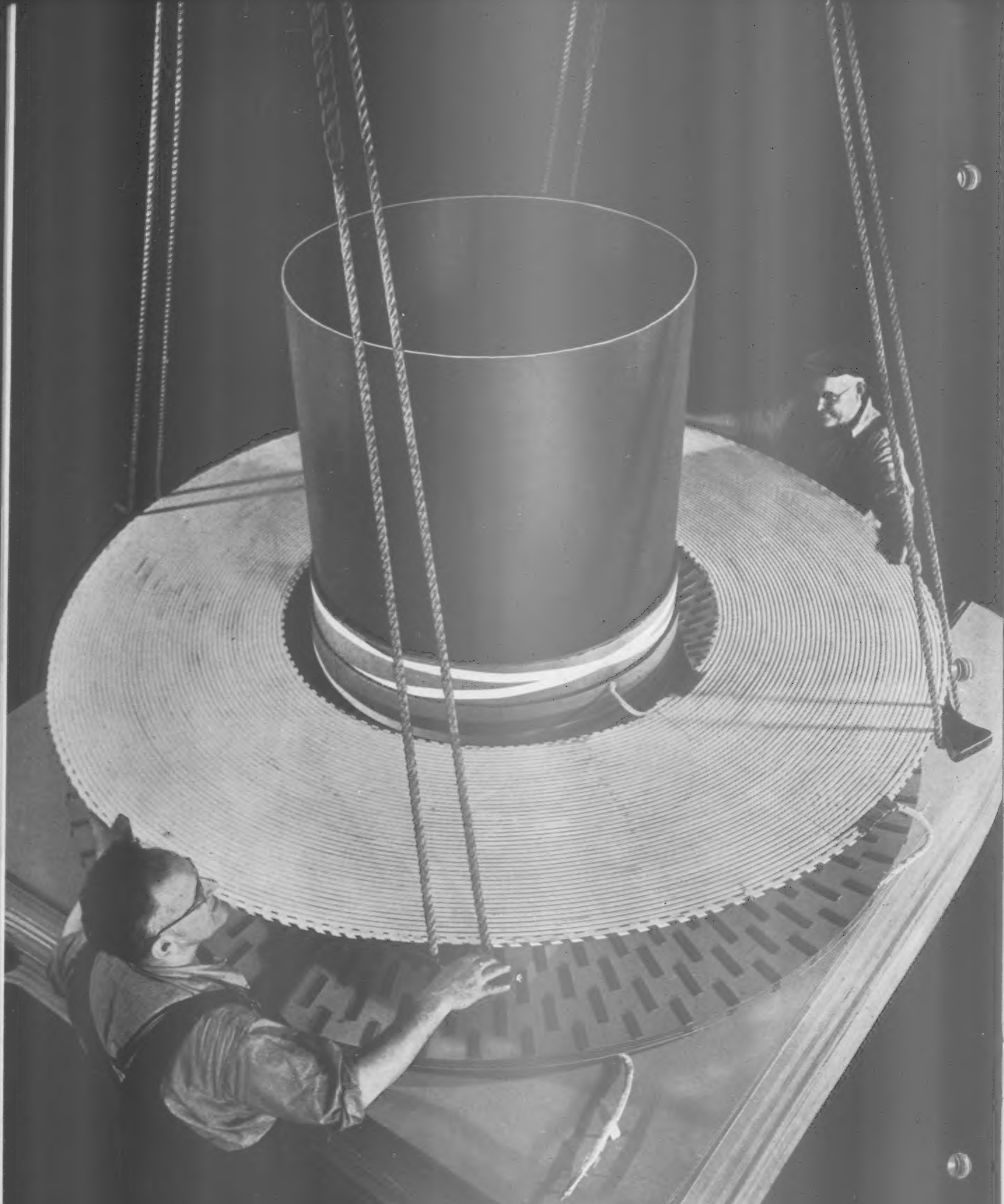
CALIPER OPENING of .010 inch is clearly visible between two one-inch slabs of steel. Reproduction was made from film spaced 10/3 of the distance from the betatron to the object. Enlargement on film was then 3.3 **(FIGURE 8)**



SECTION THROUGH FORGING ranging from 11 in. to 5 in. in thickness. Flaw shown was found to average about .005 in. in width. **(FIG. 9)**



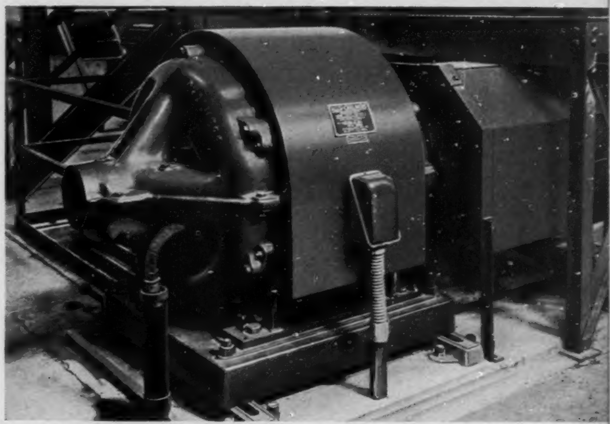
DEFECTIVE VALVE STEM is clearly shown in this radiograph taken through auto engine. Note detail in screw threads at top and piston ring clearances. **(FIG. 10)**



COILS AND INSULATION for the highest voltage transformer ever built for South America by Allis-Chalmers resemble a giant top hat. Thirty-four concentric layers of copper coil, paper-tape bound, and more than 150 layers of fuller board insulation washers are stacked seven feet high around the plastic center tubing to make the nine-foot diameter coil assembly. The transformer will be lightning-tested at 1,210,000 volts before shipping.

How to Calculate Losses in Wound Rotor Motors

R. C. MOORE
Electrical Department
Allis-Chalmers Mfg. Co.



A MINE-MILL-SINTERING plant, producing 300 tons hourly, uses this 300 hp induction motor to drive a cone crusher.

Operating characteristics and efficiency of standard wound rotor induction motors can be predicted with accuracy on the basis of this data.

WHEN reduced speed operation of fans, pumps, etc., is desired, polyphase wound rotor induction motors are commonly used to provide speed regulating by means of secondary control. Probably the most familiar method of obtaining such operation is by inserting external resistance in the secondary or rotor circuit of the motor.

The average user, although recognizing that the added resistor losses reduce the motor efficiency, does not have a complete understanding as to how or why this is brought about. The following, therefore, should provide a basis for a better understanding of wound rotor motor performance.

Product of parts is important

In order to provide a more general understanding of wound rotor motor performance, overall motor efficiency should be first determined. Power flows from the supply lines, through the stator across the air gap, and through the rotor to the motor coupling. Of course, some power is lost en route, but the essential point is that the stator and rotor can be considered to be in series electrically. Each part has its own efficiency which is, of course, the ratio of the output to the input of that part. For example, the stator output is simply the line input to the stator minus the stator losses and the stator efficiency is stator output divided by stator input. The stator power output appears at the air gap of the motor and is the power input to the rotor. Rotor efficiency is, therefore, shaft output divided by rotor input. Expressed in equation form, the overall motor efficiency for any speed and load is:

$$\text{Motor efficiency} = \text{stator efficiency} \times \text{rotor efficiency} \quad (1)$$

This is an equation which provides the basis for a considerable amount of information regarding speed regulation of induction motors.

A study of the friction clutch shown in Figure 1 reveals that when the clutch is engaged a torque "T" can be transmitted through the device. Assuming speeds N_1 and N_2 are unequal, or that there is slippage between the clutch members, then

$$\text{Hp output} = \frac{T \times N_2}{5252} \qquad \text{and Hp input} = \frac{T \times N_1}{5252}$$

where N is in rpm and T is in lbs. ft.

The efficiency of the clutch is output over input or simply the ratio of the speeds of the two halves of the clutch:

$$\text{Efficiency} = \frac{N_2}{N_1}$$

Now the operation of an induction motor, either cage or wound rotor, is similar to the friction clutch of Figure 1 where slippage occurs at the air gap of the motor. Hence,

$$\text{Rotor Efficiency} = \frac{N_2}{N_1}$$

N_1 is the synchronous speed of the rotating field and N_2 is the actual rotating speed of the motor shaft. Expressed in directly readable form induction motor rotor efficiency is:

$$\text{Rotor Efficiency} = \frac{\text{actual motor shaft speed}}{\text{motor synchronous speed}} \quad (2)$$

This expression holds true for cage or wound rotor polyphase induction motors for any speed. An electrical approach

THIS STATOR is part of a 600 hp, 3800 volt wound rotor induction motor going to a foreign rubber mill.

BY APPLYING RESISTANCE in the secondary winding of the rotor of the 600 hp wound rotor motor, shown from slip ring end, speed variation is obtained.

to the determination of equation (2) provides the following discussion:

The rotor loss in an induction motor, cage or wound rotor, is given in the A.I.E.E. "Test Code for Polyphase Induction Machines No. 500" as:

Motor rotor I^2R loss = secondary input × slip...... (3)

where slip is expressed as a decimal fraction. For example, a slip of 0.10 for a 500 rpm (synchronous speed) motor means a departure of 50 rpm from synchronous speed or an actual motor operating speed of 450 rpm. If secondary input is in Hp then motor rotor I^2R loss is in Hp. The same reasoning applies if kw values are used.

Obviously, secondary (that is, rotor) input is the sum of the rotor output plus the rotor losses. Thus:

Rotor input = rotor output + Rotor input × slip... (4)

Thus:

$$\text{Rotor Efficiency} = \frac{\text{Rotor output}}{\text{Rotor input}} = 1\text{-}S =$$

percent of synchronous speed.................. (5)

Equation (2) and (5) can be shown to be identical.

Motor synchronous speed depends on the number of poles for which the winding is designed and the stator supply line frequency. To facilitate the use of equations (2) and (5) the list of motor synchronous speeds (see table opposite) has been provided for commonly used windings and frequencies.

Slip for maximum rotor loss

It is frequently of interest to know the motor speed or slip at which *maximum* rotor loss occurs. The mathematical analysis is not difficult and readily provides the desired solution. Equation (3) when restated is:

$$\frac{\text{Rotor loss}}{S} = \text{rotor input} = \text{rotor loss} + \text{rotor output}$$

$$\text{Rotor loss} = \frac{\text{rotor output} \times S}{1\text{-}S} \quad \text{Where } S = \text{Slip}$$

In familiar Hp terms the equation is:

$$\text{Hp Rotor Loss} = \frac{Hp_o \times S}{1\text{-}S} \quad \text{.....................(6)}$$

Where Hp_o is Hp output of rotor. Strictly speaking, the Hp output is the coupling output plus motor windage and friction. However, in most cases it is permissible to use simply the delivered coupling Hp of the motor for Hp_o.

Expression (6) is in a form which can be advantageously used to determine the slip or speed at which maximum rotor loss occurs. While this determination may be of somewhat

	SYNCHRONOUS SPEEDS (RPM)	
Poles	25 Cycles	60 Cycles
2	1500	3600
4	750	1800
6	500	1200
8	300	900
10	300	720
12	250	600
If P = Poles	Syn. Speed = $\frac{3000}{P}$	Syn. Speed = $\frac{7200}{P}$

academic interest, it serves to increase understanding of problems involved when motors are applied to loads having different speed characteristics. Typical examples are those cases where the Hp load varies as the cube of the speed, as the square of the speed, etc.

(A) Hp load varies as cube of speed

The actual Hp_o at reduced speed operation can be expressed by means of the following formula:

$$Hp_o = Hp_{f.l.} \times \left(\frac{\text{actual rotor speed}}{\text{full load speed}}\right)^3 = Hp_{f.l.} \times (1\text{-}S)^3$$

Here "S" is slip in decimals and $Hp_{f.l.}$ is full load Hp at full speed (no external resistance in the rotor external circuit).

Using equation (6):

$$\text{Hp Rotor Loss} = \frac{Hp_{f.l.}\ (1\text{-}S)^3 \times S}{(1\text{-}S)} = {}^* Hp_{f.l.}\ (1\text{-}S)^2 \times S$$

If the curve of rotor loss is plotted against slip then a curve like that in Figure 2 is obtained. Obviously the maximum value of rotor loss is obtainable when the tangent to the curve lies horizontal, that is, the slope of the curve is zero.

Mathematically then,

$$\frac{d}{ds}\ (\text{Hp Rotor Loss}) = Hp_{f.l.}\ (1\text{-}4S + 3S^2) \ldots . (7)$$

When the derivative is zero, that is, when the tangent to the curve in Figure 2 is horizontal, then the rotor loss is maximum. Expressed mathematically, equation (7) can be made equal to zero as follows:

$$\frac{d}{ds}\ (\text{Hp" Rotor Loss}) = Hp_{f.l.}\ (1\text{-}4S + 3S^2) = o$$

$$1\text{-}4S + 3S^2 = o \qquad (3S\text{-}1)\ (S\text{-}1) = o \qquad S = 1 \text{ or } \frac{1}{3}$$

Hence maximum rotor power loss occurs at $33\frac{1}{3}\%$ slip or $66\frac{2}{3}\%$ speed. The curve of Figure 2 is also tangent to the horizontal axis at $S = 1.0$.

(B) Hp load varies as square of the speed

In this case the same reasoning is applied as in case (A).

$$Hp = Hp_{f.l.} \times \left(\frac{\text{Actual Rotor Speed}}{\text{Full Load Speed}}\right)^2 = Hp_{f.l.}\ (1\text{-}S)^2$$

Substituting in equation (6):

$$\text{Hp Rotor Loss} = \frac{Hp_{f.l.}\ (1\text{-}S)^2 \times S}{1\text{-}S} = Hp_{f.l.}\ (1\text{-}S)\ S$$

If the curve of rotor loss is plotted against slip then a curve as shown in Figure 3 is obtained:

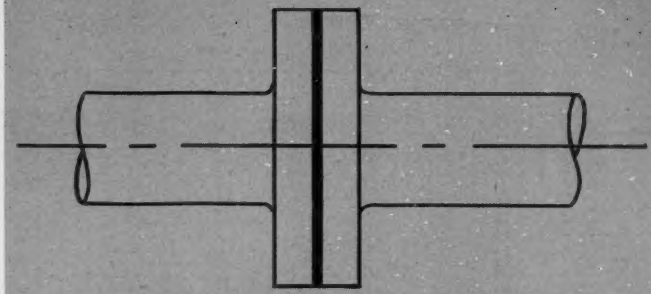
$$\frac{d}{ds}(\text{Hp Rotor Loss}) = \frac{d}{ds}\left[Hp_{f.l.} \times S\ (1\text{-}S)\right]$$

or $1\text{-}2S = o \quad S = \frac{1}{2}$

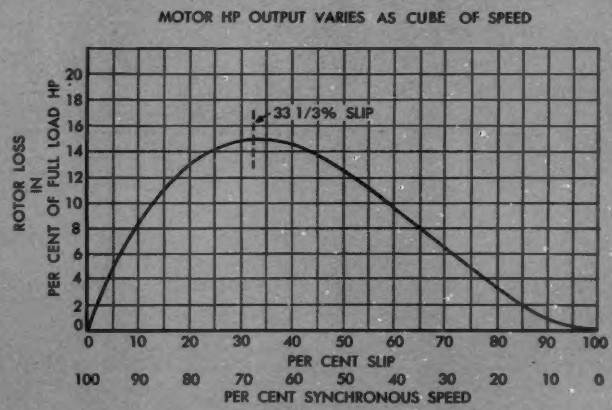
Hence maximum rotor power loss occurs at 50% slip or 50% speed.

(C) Hp load varies directly as speed — constant torque load

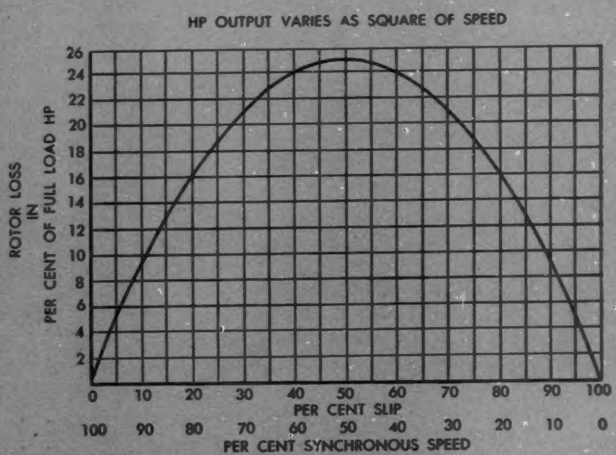
$$Hp_o = Hp_{f.l.} \times \frac{\text{Actual Rotor Speed}}{\text{Full Load Speed}} = Hp_{f.l.}\ (1\text{-}S)$$



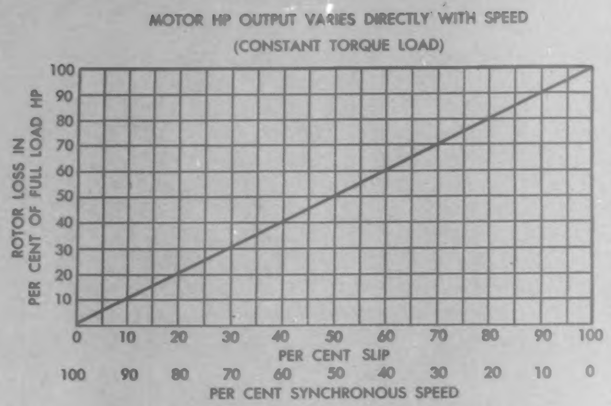
SIMPLEST FORM OF FRICTION CLUTCH represents slip and torque factors in an induction motor. **(FIGURE 1)**



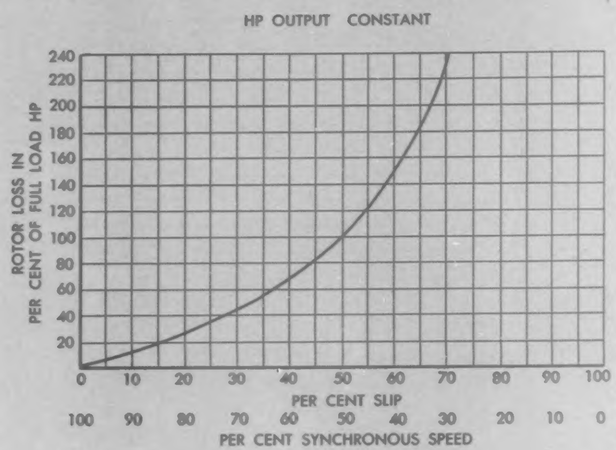
INDUCTION MOTOR ROTOR LOSS for loads where horsepower output varies as cube of speed. **(FIGURE 2)**



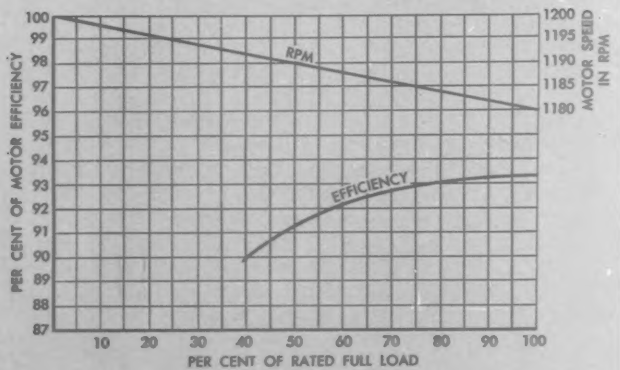
INDUCTION MOTOR ROTOR LOSS where horsepower output varies as square of speed. **(FIGURE 3)**



INDUCTION MOTOR ROTOR LOSS where horsepower output varies directly with speed. **(FIGURE 4)**



INDUCTION MOTOR ROTOR LOSS where constant horsepower is required at all speeds. **(FIGURE 5)**



EFFICIENCY AND SPEED of typical 1200 rpm, 500 hp induction motor at various loads. **(FIGURE 6)**

Substituting in equation (6):

$$\text{Hp Rotor Loss} = \frac{Hp_{f.l.}\ (1\text{-}S) \times S}{1\text{-}S} = Hp_{f.l.} \times S$$

The rotor loss is plotted in Figure 4 showing that the loss is maximum at zero speed.

(D) Hp load constant for varying speeds — constant hp load

$Hp_o - Hp_{f.l.}$

Substituting in equation (10):

$$\text{Hp Rotor Loss} = \frac{Hp_{f.l.} \times S}{1\text{-}S}$$

The rotor loss is plotted in Figure 5, showing rotor loss rises very rapidly with speed reduction.

Calculating stator efficiency

Since the stator is a non-rotating member, stator efficiency is not as simply obtained as the expressions for rotor efficiency in equations (2) and (5), however, from equations (1 and (5):

$$\text{Stator efficiency} = \frac{\text{Motor efficiency}}{1\text{-}S} \quad \text{.............} \quad (8)$$

Normal efficiencies at one-half, three-quarters and full loads, for motors of standard hp ratings, speeds and frequencies, as well as the full-load speed, is commonly published information. The full-load stator efficiency is therefore readily calculated as

$$= \frac{\text{Motor efficiency at Full Load}}{1\text{-}S}$$

$$\text{Where } 1\text{-}S = \frac{\text{Operating Speed}}{\text{Synchronous Speed}}$$

Using this relationship the following efficiencies can be obtained:

When a constant torque load is carried with the load Hp varying directly with speed, the stator current and hence the stator efficiency remains unchanged with speed. Thus, stator efficiency determined by using the published normal full load value can be used for all further calculations for reduced speed operation.

As the torque varies the stator efficiency will also vary. If load torque varies as the *square* of the speed, then at 70.7% speed the load torque is 50% of its full speed value. The stator efficiency is the published normal efficiency at one-half load, as published, divided by (1-S), where "S" is also one-half of its value at full load (See Equation 8).

If the motor operates at 86.6% speed then the load torque is $(.866)^2$ or three-quarters of its full load value. The stator efficiency is then the motor published normal efficiency at three-quarter load, as published, divided by 1-S, where "S" is three-quarters of its value at full load.

When determination of stator efficiency requires motor efficiencies not published, the data can readily be obtained from the factory or from a curve plotted from published normal values.

The discussion may be extended to load torques which vary as some other function of speed. For example, if the load torque varies as the cube of the speed, then at 79.3%

speed, the load torque is 50% of its full speed value, the stator efficiency to be substituted in equation (1) is the published normal efficiency at one-half load, as published, divided by (1-S), where "S" is also one-half of its full load value.

Examples using the methods just developed will illustrate their usefulness.

Examples using methods

A 500 Hp, 3 phase, 60 cycle, wound rotor motor runs at 1180 rpm at full load (synchronous speed is 1200 rpm for this 6 pole, 60 cycle motor) published normal motor efficiencies are for one-half, three-quarters and full load respectively, 91.3, 93, 93.3 percent (See Figure 6).

Prob. 1 If the load is constant torque (such as some reciprocating device) at all operating speeds, what is the motor efficiency at any given operating speed when speed regulating?

Prob. 2 If this motor is applied instead to a type of fan load, where torque varies directly as speed, what are the motor efficiencies at 85% and 70% speeds?

Prob. 3 If the load is a pump with torque varying as the square of the speed (Hp therefore varies as the cube of the speed), what is the efficiency at 85% and 70% speed?

Solutions to problems

Prob. 1 Let 70% and 85% speeds be chosen to get a comparison with the results in Prob. 2 and 3.

(a) Refer to the efficiency curve of Figure 6 and note that at full load stator efficiency (at full load) =

$$\frac{93.3}{1\text{-}.0166} = 94.87$$

where "S" is slip and is the rpm departure from synchronous speed (1200-1180 = 20 rpm) divided by synchronous speed.

It will be recalled that for constant torque loading the stator efficiency remains unchanged at all regulating speeds, a fact which simplifies calculations considerably.

At 70% Speed (S = 1.00-.70)

Motor Efficiency = 94.87 (1.00-.30) = 66.41% (See Equations (1) and (2))

or simply

Motor Efficiency = 94.87x% Rotor Speed (See Equation (6))

Hence at 85% Speed

Motor Efficiency = 94.87 × .85 = 80.64%

A rough approximation which quickly checks the calculations can be made. The approximation assumes that at full load the published normal full load efficiency is divided equally between stator and rotor — that is, stator efficiency = the square root of the published normal Efficiency.

At 70% Speed

$$\text{Motor Efficiency} = \sqrt{.933} \times .70 = .676 \text{ or } 67.6\%$$

At 85% Speed

$$\text{Motor Efficiency} = \sqrt{.933} \times .85 = .82 \text{ or } 82\%$$

Prob. 2 Since the load torque varies linearly with speed, the stator efficiency for 70% speed operation must be obtained from Figure 6 for a Hp load of 70% of full load. A value of 92.8% is obtained for motor efficiency and 1186 for motor rpm. Motor speed is then 98.8%. Hence from equation (8)

$$\text{Stator Efficiency} = \frac{92.8}{.988} = 93.9\%$$

Motor Efficiency at reduced speed is

Motor Efficiency = 93.9 × .70 = 65.73% at 70% speed.

(Using the rough check method)

$$\text{Motor Efficiency} = \sqrt{92.8} \times .70 = 67.4\%$$

85% Speed

Motor Efficiency from Figure 6 = 93.2%

Motor rpm = 1183; Percent motor speed = 98.6

Stator Efficiency = 93.2/.986 = 94.5

Motor Efficiency = 94.5 × .85 = 80.3% at 85% speed.

(Rough check, motor efficiency = $\sqrt{93.2} \times 85 = 82\%$)

Prob. 3 Since torque varies as the square of the speed the stator efficiency for 70% speed must be obtained from Figure 6 for a Hp load of $(.70)^2 \times 100$ or 49% load. A value of 91.2 is obtained and the corresponding motor speed is 1190.5 rpm (Percent speed = 99.5%). Performing all operations at one time then, at 70% speed,

$$\text{Motor Efficiency} = \frac{91.2}{.995} \times .70 = 64.1\%$$

(Rough check, motor efficiency = $\sqrt{.912} \times 70 = 66.6\%$)

85% Speed

Motor Efficiency, Figure 6, for $(.85)^2 \times 100 = 72.25\%$ load, is 92.9 Motor rpm at 72.25% load = 1186, or percent speed = 98.8

$$\text{Motor Efficiency} = \frac{92.9}{.988} \times 85 = 79.9\%$$

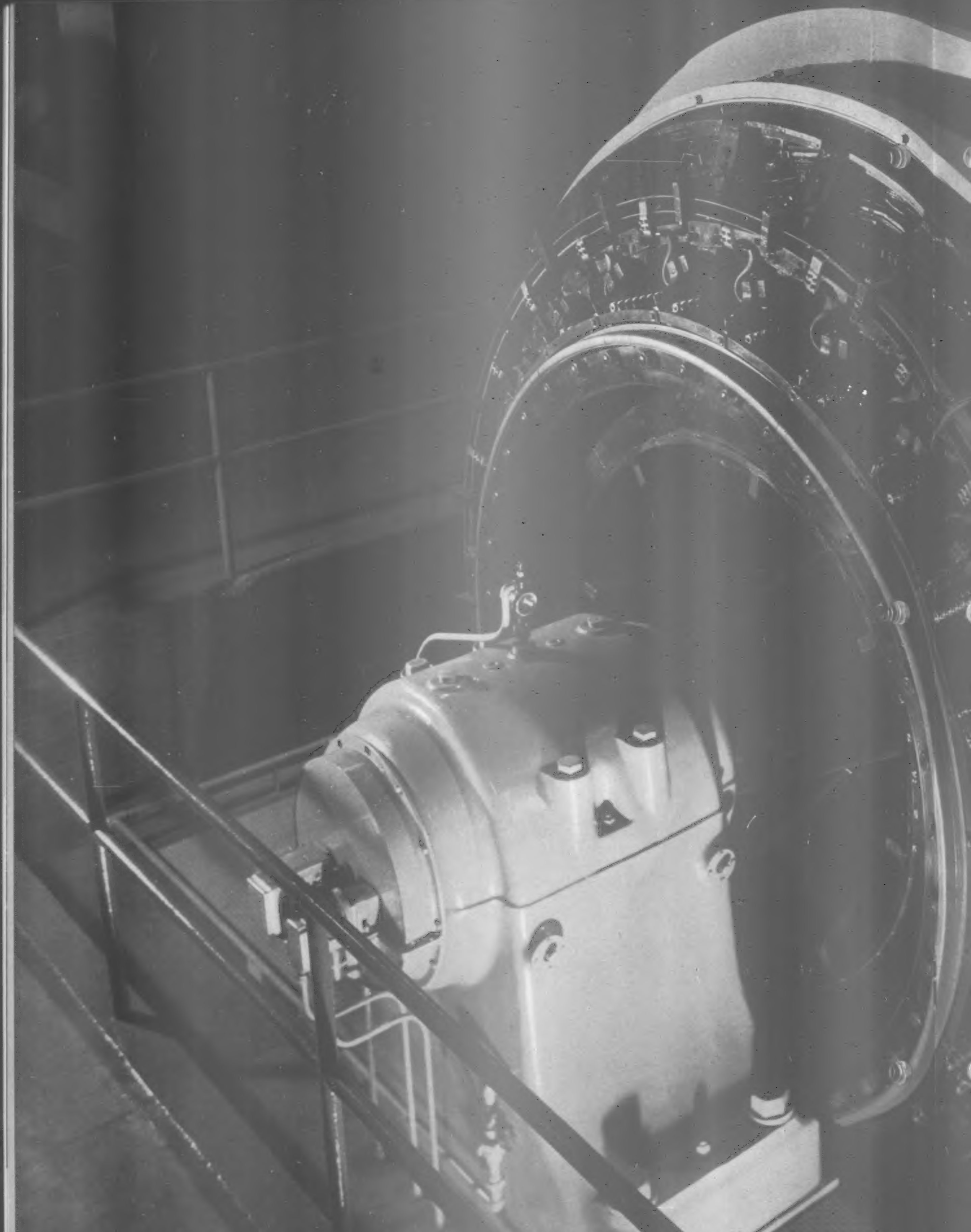
(Rough check, motor efficiency = $\sqrt{.929} \times 85 = 81.9\%$)

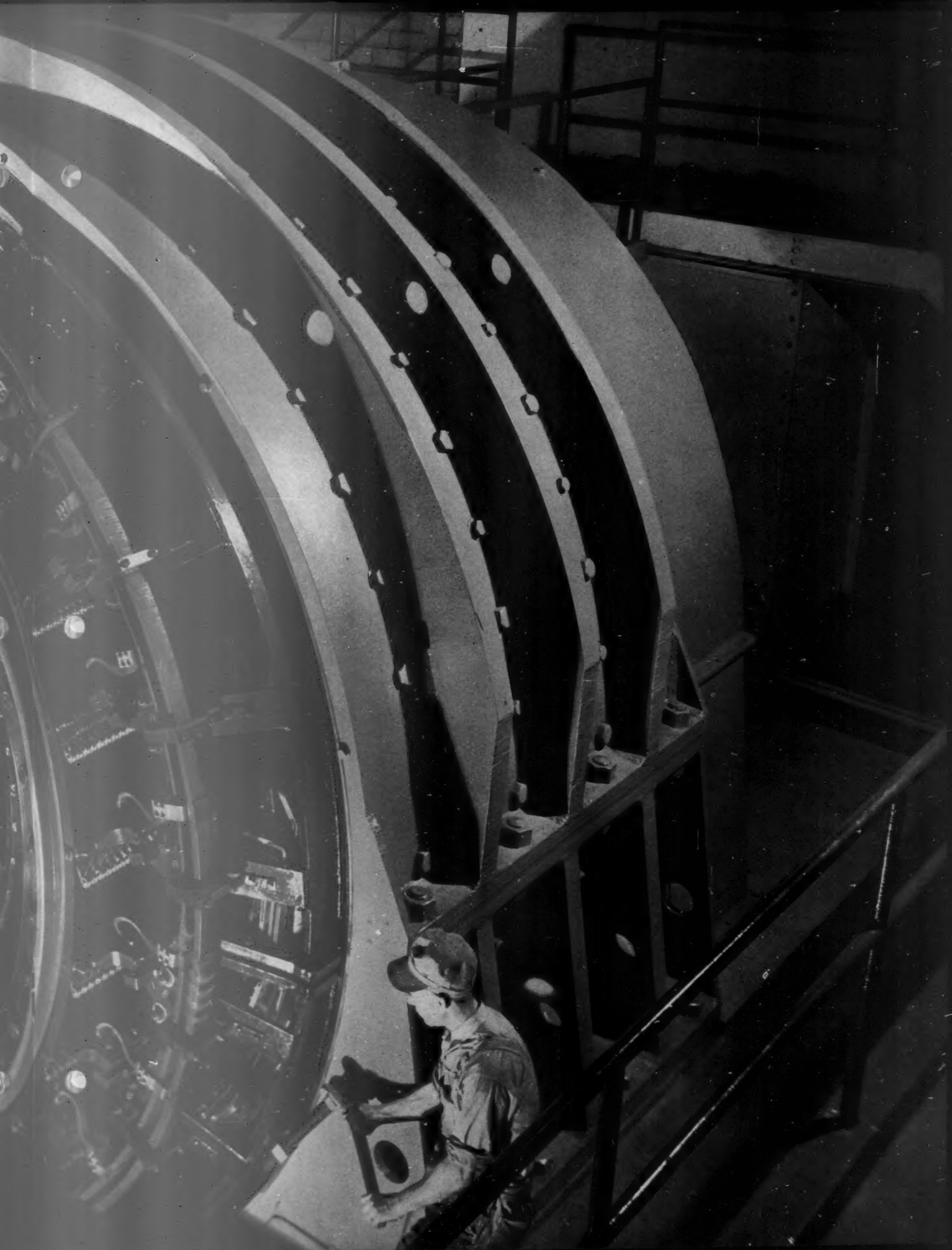
The results for the three problems, when tabulated, are:

	% Efficiency T, Constant	% Efficiency $T \propto$ Speed	% Efficiency^2 $T \propto$ Speed
70% Speed	66.41	65.73	64.1
85% Speed	80.64	80.3	79.9

Thus we see that evaluating motor efficiencies at reduced speeds is not difficult if a few elementary characteristics of the machine are considered.

PHYSICALLY ONE OF THE LARGEST motors in the country for operating reversing blooming mills in steel plants, this Allis-Chalmers 7000 horsepower direct-current motor reverses a 44 inch mill full speed forward to full speed reverse in only seven seconds. During reversal the accelerating current peak is limited to a predetermined value by Regulex control.

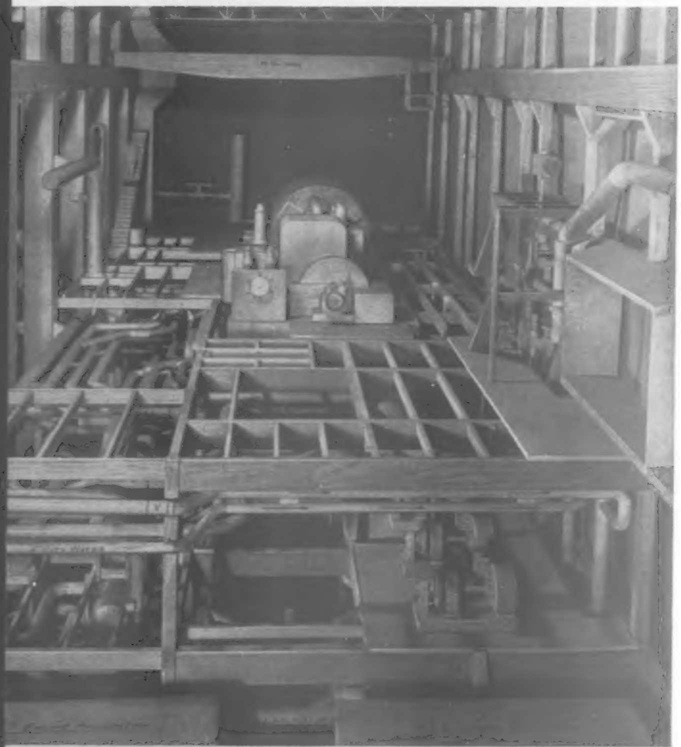




MODELS BUILD BETTER POWER PLANTS

F. L. DORNBROOK
Chief Engineer of Power Plants
Wisconsin Electric Power Company

Exhibition models of proposed power plants are not new—but *working* models, as accurate as an assembly drawing, help this Milwaukee utility to build the world's most efficient steam power plants.

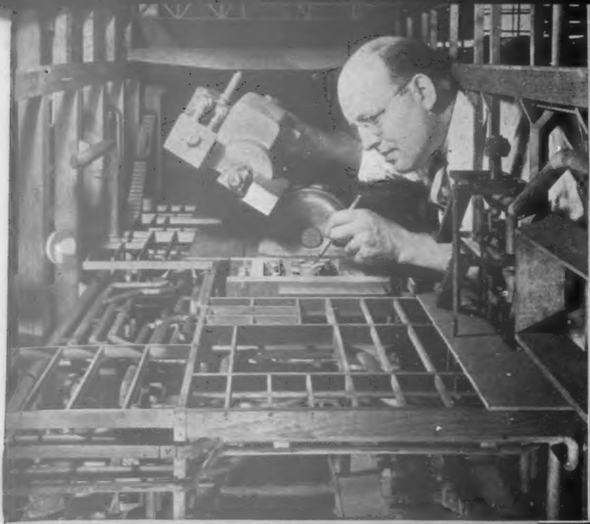


COMMERCE STREET PLANT MODEL shows the details of piping and equipment in turbine room and on the lower floors. Floor and some of piping has been removed in order to obtain a clear photograph.

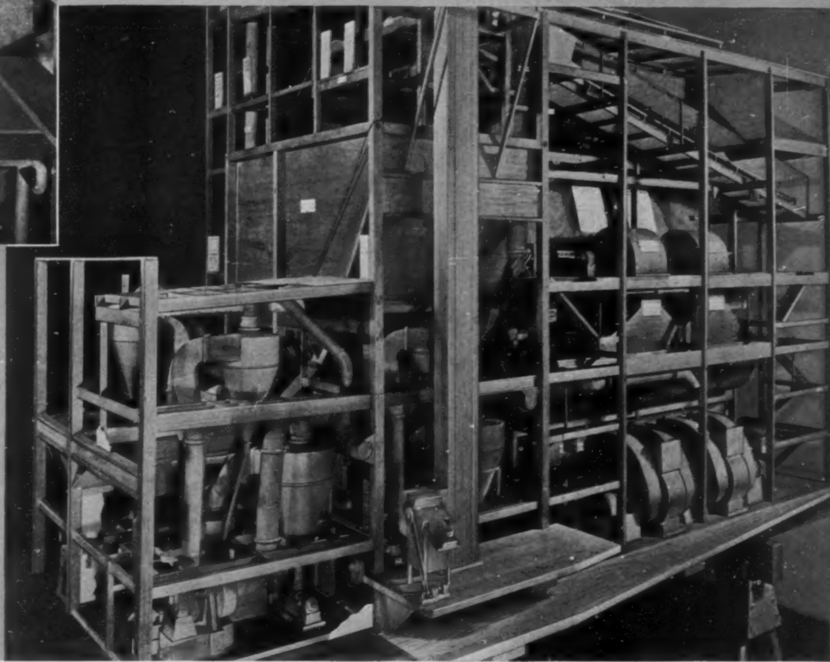
TURBINE ROOM VIEW from same position as above shows similarity. Problems of interference are more serious on lower floors. A working model was of particular value in this installation where a 35,000 kw turbine had to be fitted into an existing plant replacing obsolete equipment.

AN old Chinese philosopher is reported to have said "A picture is worth 10,000 words" and the present development of photography proves that the old gentleman was right about pictures. But you cannot photograph an idea—you have to draw a picture of it laboriously from your imagination. Since it is not possible to draw a picture in true perspective without distortion, the draftsmen have invented a standard method of projecting top views, side views and end views from which the reader, by means of mental gymnastics and study, can obtain a crude picture of the idea.

The method of drawing three views is satisfactory for simple and single objects, but the trouble really begins when a complicated layout must be shown by drawings. Take, for example, a power plant in which equipment, connecting piping, air ducts, platforms, stairways, building walls and foundations must be shown in true relation. To make or read such drawings requires mental concentration of the highest order.



PIPING DETAILS can be analyzed easily in working model. This turbine has steam extraction points for heating downtown area. Several extraction points are provided to maintain efficiency at different loads.



FULL VIEW OF WORKING MODEL shows the section devoted to coal handling equipment, boilers and blowers. This model (Port Washington No. 2 — 80,000 kw) was so large that turbine and condenser sections were built separately for simplicity. Addition in left foreground was designed during war to handle unforeseen coal problems — was not actually built. Each model is provided with canvas canopy to keep out dust.

The mind becomes fatigued by a continuous orientation and often ideas are lost in the shuffle of many drawings.

Because of those limitations of drawings, the Engineering Department of the Wisconsin Electric Power Company has found it profitable to construct a model to scale whenever a new power plant or a major addition is planned. This procedure was started on a small scale back in 1926 and has proved so successful that it is now standard on all major power plant changes or additions.

Simplicity is essential

These models are not intended for exhibition, they are working models made coincidentally with the drawings. Fussy details like hand railings or flanges on "I" beams have been eliminated for the sake of economy and simplicity.

The most practical scale has been found to be ½ inch equals 1 foot. A base of plywood board is set on saw horses and the model is built up of patternmakers' pinewood strips and blocks which can be cut, turned and carved easily. Parts are fastened by dowels, nails and glue. Wax was found unsuitable because it creeps out of shape in hot weather. Major items like turbines, condensers, pumps, motors, boilers, fans, heaters and tanks are carved from wood blocks to approximate shape and to true overall scale. Piping is wood-turned to required diameter including the insulation covering. Pipe bends are segments cut from doughnut-shaped rings turned on a lathe. A strip of canvas represents a coal belt conveyor. A wooden disc on a nail becomes a valve handwheel. Floor gratings are made from expanded metal lathing. Instruments are drawn on a panel board which is a block of wood. Stairways are notched strips of wood. Parts of the model are made removable where necessary to show construction beneath floors.

An ingenious model builder will find a way, and our Company fortunately has such a man. He is a draftsman with patternmaking experience, and he enjoys making things as a hobby. He has a good set of wood-working tools—chisels, saws, cutters, drills, etc. A band saw, jig saw and drill press are useful aids. Close cooperation with the Company's pattern shop provides a source for materials and lathe work. The model is built in a room adjacent to the drafting room so that the draftsmen have ready access and can work closely with the model builder. In this room, "No Smoking" is the rule, and a portable extinguisher is handy just in case. In addition, all models are given a fire resistant treatment as soon as they are completed.

There are a number of obvious advantages gained by building a model. Clearances can be provided to handle items of equipment during construction, and later to handle parts when dismantling is required for maintenance; clearances for replacement of tubes in condensers, coolers, boilers and heaters; clearances to handle motors, fan wheels and heavy parts by means of tackle and cranes. Many useless steps by the operators can be saved by placing stairways, platforms, valves,

dampers, instruments, motor starters, etc., in the most efficient locations. Because the operating life of a power plant is 30 to 40 years, this should be a major consideration in every design.

Interferences are avoided between piping, duct work and building steel and such interferences are most difficult to visualize from drawings. It is possible by avoiding one major interference during the construction of a plant to save an amount equal to the entire cost of the model, in addition to avoiding a critical delay in completing the installation.

The exact cost of a model has never been determined, however a typical miniature such as that shown on page 23 takes a model builder about 18 months working 6 to 8 hours a day on the model.

Models save costly errors

A few instances of the advantages gained using the model might be of interest. On the first 80,000 kw unit at the Port Washington plant, we felt that bids for the installation of a number of 17 foot diameter surge tanks were higher than necessary. A discussion with one of the subcontractors brought out that he had added a safety factor to the bid to offset cost of installing the tanks section by section with the usual delays from interference with other work being done simultaneously. In a few minutes spent examining the model, we were able to show him how the parts could be fabricated at their plant and slid into place through a nearby bay section which could remain open until a predetermined date on the erection schedule. A new bid was submitted several thousand dollars lower and the tanks went in on schedule without a hitch.

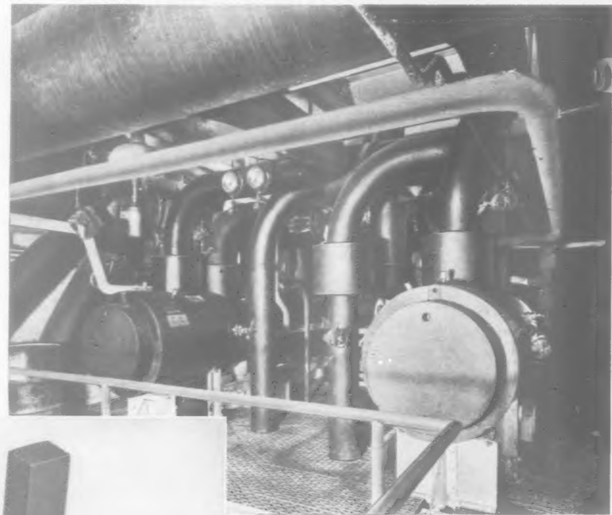
On a later addition, which doubled the capacity of the original Port Washington plant, we found that model dimensions had enabled us to make very accurate estimates of the amount of piping required. Although over 3,000 feet of high pressure steam line were required, our piping fabricator did not have a single full length of any size pipe left after the job was complete.

The model serves as means for checking and proving what is shown on drawings. After the idea is drawn on paper, it must be reproduced by the model builder before any orders for material and fabrication are released for the actual construction work. In the event of a mistake in the drawing, obviously, it is much cheaper for the model builder to change or recut a piece of wood than to make the costly correction in the field.

A model thus becomes a super-assembly of all drawings. It automatically orients the reader, and no explanations of the design are needed to preface a discussion of any part. The model itself invites suggestions, and improvements are often proposed by those who are interested but who cannot take the time and effort to study all the drawings.

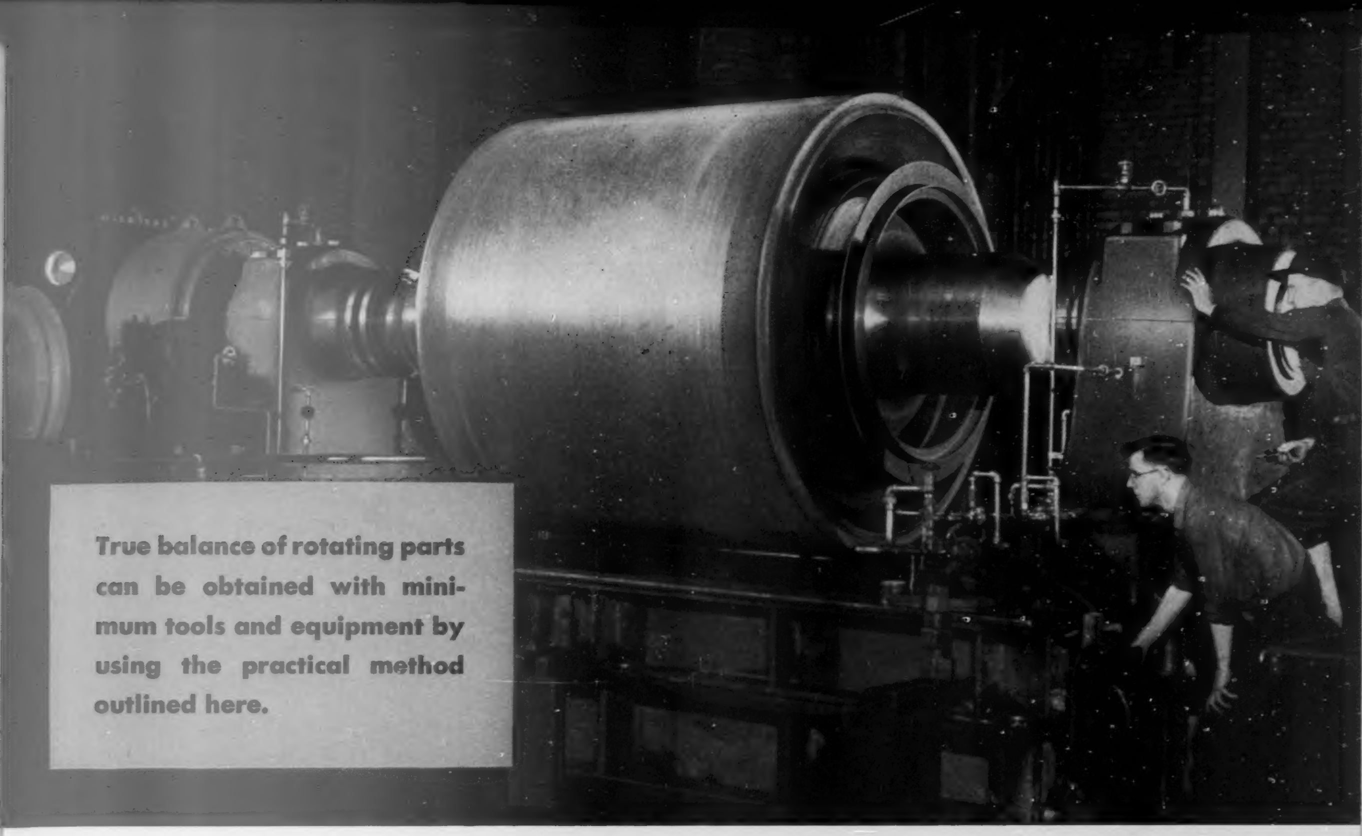
Models are retained in a storeroom, convenient to the office, for future reference. This becomes especially useful when the plant is located too far away for quick checking of some detail such as the space available for some additional item of equipment. When not in use the models are protected from dust by canvas covers which can be tied at the corners or rolled up to expose a side or all sides.

Our experience has convinced us that working models are just as valuable in the proper design of a power plant as drawings or specification sheets.



TYPICAL OF CROWDED AREAS in many power plants are scenes such as this. By careful design and use of models, problems of clearances, safety and convenience can be overcome under adverse conditions.

BASIC ELEMENTS and some of the simple assemblies are shown here. Model room stock includes most standard sizes of piping and fittings. Changes or addition to models then becomes simple matter.



True balance of rotating parts can be obtained with minimum tools and equipment by using the practical method outlined here.

WHEN THE ROTOR of a synchronous condenser, for instance, is too large to balance by machine it is run on its own base and bearings. Exciter is at left of the rotor and starting switch for oil pump at right. Speed is checked with a tachometer, the average test requiring about 50 minutes.

Balancing Is Easy...

If You Know How

W. F. KING
Mechanical Engineer, Electrical Department
Allis-Chalmers Mfg. Co.

★

ALTHOUGH machine balancing of rotors has been perfected to a high degree of precision, situations occur where balancing by hand is necessary. For instance, some rotors are too large to be handled in balancing machines, others require balancing at an operating speed which may be beyond the balance machine's limits, and some may need balancing after repairs in the field where a balance machine is not available.

Hand balancing can be a tedious and discouraging process to one inexperienced with the basic rules of balance. However, with a knowledge of these rules and with relatively simple equipment, most cases of unbalance may be solved.

The response of a rotor to balance weights generally follows simple rules. While it is possible to balance some rigid rotors from the data obtained in three runs, deviation from proportionality renders direct mathematical solution impossible in other cases. The method to be explained here consists of balancing in direct, successive steps.

The forces resulting from unbalance are proportional to the amount of unbalance, expressed as weight times radius (ounce inches), and the square of the rpm. Hence the refinement of balance must improve as the speed is increased. The axis of the rotor travels in an orbit determined by the unbalance forces and the flexural resistance of rotor, bearing supports, base and foundation. Movement of the bearing support is usually used as a measure of the unbalance.

Rotor form decides form of unbalance

Unbalance can exist in various modes, depending on the configuration of the rotating body. Assuming a two-bearing system, the unbalance may occur as shown in Figure 1. Two or more discs represent a long rotor. Static unbalance, Figures 1a and 1b, so called because it can be detected by resting the shaft on rails or rollers, is generally all that requires correction when the length of the rotor is small compared to the diameter as in the case of a low speed synchronous motor. Dynamic unbalance, Figure 1c, which can be detected only by a rotational test, produces forces on the two bearings which are opposite in phase. Usually, unbalance occurs as a combination of static and dynamic unbalance, Figure 1d.

In the case of a long, flexible rotor such as that of a turbo generator, represented by three discs in Figure 1e, the deflection of the shaft caused by the unbalance is enough to add appreciably to the unbalance. Since this deflection is a function of the rotational speed, the rotor if balanced in only two axial locations, such as the two outer discs, can be balanced for only one speed. A similar condition occurs in the case of a rotor with an overhung disc, Figure 1f, which can be best handled by balancing the overhung element separately.

The vibration data necessary for balancing is first, the amplitude of vibration and, second, the angular phase relationship of the vibratory movement to the rotating body; in other words, the high spot. Vibration "pick-ups" used to determine amplitude of vibration are designed to have a low natural frequency compared to the frequency of the vibration measured and hence may be considered stationary in space relative to the vibrating object.

Probably the simplest form of vibrometer consists of a weighted dial indicator supported on light springs or sponge rubber with the stem of the indicator in physical contact with the bearing housing. In another type, a small concave mirror is oscillated through a mechanical linkage by the vibratory movement, which it greatly magnifies by reflecting a beam of light on a ground glass scale. The electrical pick-up which is available in various modifications permits readings with more accuracy and has more adaptability than the mechanical types but is not as readily applied. In these devices an emf is generated by a coil of fine wire moving in unison with the vibrating body within the field of a permanent magnet which is flexibly supported. By suitable amplification any desired degree of sensitivity may be obtained. Indicating or recording instruments may be used.

How "high spot" is determined

The angular relationship can be determined by coating a portion of the shaft with whitewash and scribing that portion of the shaft lightly when it is rotating at the speed selected for balancing. Obviously the portion of the shaft scribed must be smooth and concentric with the journals. The coating of whitewash should be uniform in thickness. By this method a short, definite marking is obtained when the unbalance is large but the accuracy diminishes as the balance is improved.

A better method employs a stroboscopic lamp which is flashed at each revolution of the shaft by means of a contact device with angular adjustment. The contact device is adjusted to cause the flash to occur at the instant of maximum deflection of a dial indicator or light beam vibrometer. At the maximum deflection setting the lamp is used to read numbers painted on the shaft. The direction in which the shaft is illuminated should preferably be the same as that in which the vibration is measured.

The phase angle may be determined more accurately by the use of a sine wave generator connected to the rotor shaft in conjunction with an electrical vibration pickup. The output of the two units is fed into a indicating instrument. By turning the stator of the sine wave generator until the voltages are in phase a maximum reading is obtained which is proportional to the amplitude of vibration. When the voltages are 90° out of phase a zero reading is obtained. Since the zero position is quite sharp it is used for finding the phase angle, which is read on a protractor attached to the stator of the generator.

It should be noted that the "high spot" of the rotor is not the heavy spot except at low speed. Furthermore, while the phase angle or angular relationship measured need not coincide with the "high spot," it must be determined in a consistent manner for all balancing runs.

Single disc on a shaft

Consider the case of a single disc supported on a shaft between bearings, Figure 1a, which can be balanced by the addition of a single weight. Vibration readings on one bearing are sufficient. Assume the measured vibration is .0037 inch at 55 degrees angular displacement. This measurement is plotted as a vector, 0-1, on a polar diagram, Figure 2a, where the length of the vector represents the amplitude to scale and the direction is that of the phase angle. A trial balance weight is added to the disc at a convenient location, assume 17 ounces at 190 degrees. This weight is plotted as a vector, Figure 2b. The vibration reading taken after adding the trial weight is .0019 inch at 150 degrees which is plotted as 0-2 on Figure 2a.

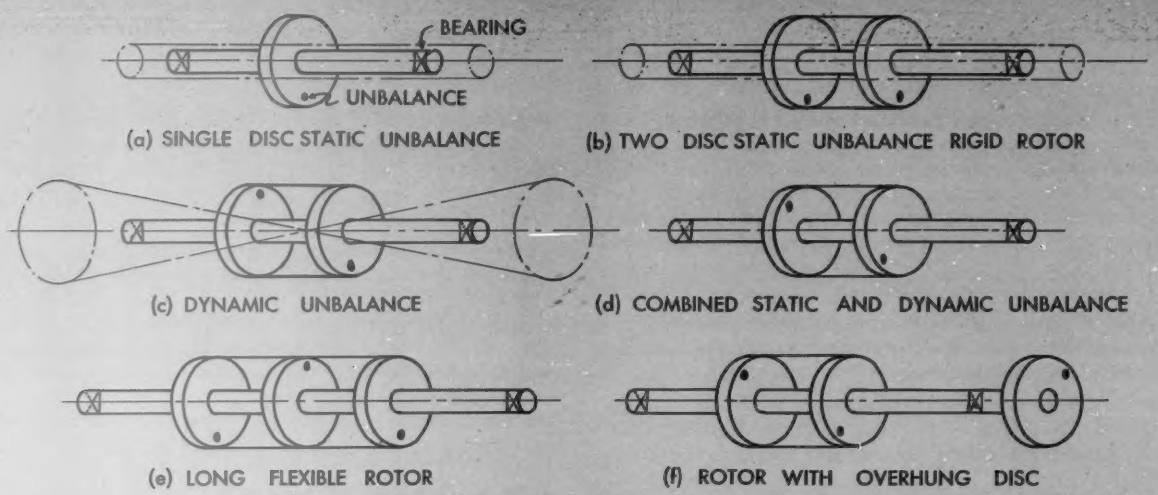
The effect of the trial weight, determined by drawing the closing line 1-2 is found to be .0043 inch in magnitude. Drawing a line through the center 0, parallel to 1-2 the direction of the effect of the trial weight is found to be 209 degrees. The effect required for correction of the unbalance is equal and opposite to the initial vibration reading, or .0037 inch at 235 degrees. The required balance correction is then obtained by replacing the trial weight with one 37/43 of 17 oz. or 14.6 oz. and by shifting the weight location 26 degrees counterclockwise, that is, locating it at 216 degrees, line 0-B, Figure 2b.

Balancing procedure is based on the assumptions that the amplitude of vibration is proportional to the unbalance and that a change in the angular location of the weight will change the effect of the weight through an equal angle. Depending on the construction of the rotor these assumptions are more or less correct. Furthermore, the accuracy of the results depends on the accuracy of the vibration measurements. For satisfactory results the effect of the trial weight should be of about the same magnitude as that of the original unbalance. If the balance correction as determined from the first trial run is inadequate the procedure should be repeated using the last check run as a trial run.

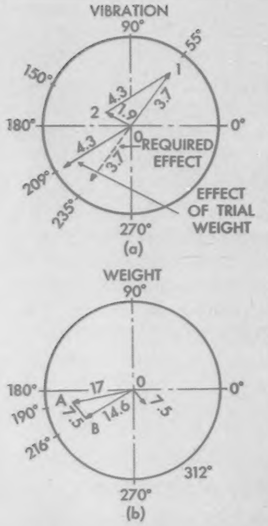
The vector representation of balance weights is helpful in combining weights when a limited number of weight locations are available. For example, if in the foregoing case it was preferable to leave the first weight of 17 oz. in place and to add another to produce a combined effect equal to O-B, the additional weight would be represented by the vector A-B, or 7.5 oz. at 312 degrees. When a weight must be transferred to a different radial location the amount of weight is changed in inverse ratio to the distance from the center of rotation. Removing a weight is the same as adding an equal weight diametrically opposite.

Rigid rotor with two discs

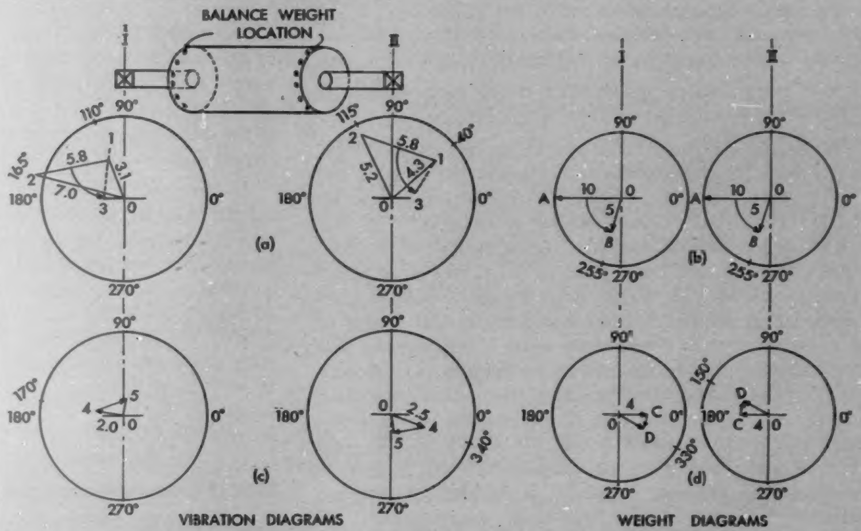
Static unbalance of a long rotor, Figure 1b, will cause vibration of equal amplitude and the same phase angle at both bearings if the rotor is symmetrical and the bearing supports are equal in mass and rigidity. Under asymmetrical condi-



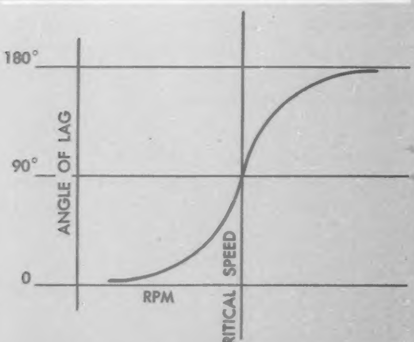
SIX MOST COMMON CAUSES OF UNBALANCE are shown above. Each presents a different problem in balancing. **(FIGURE 1)**



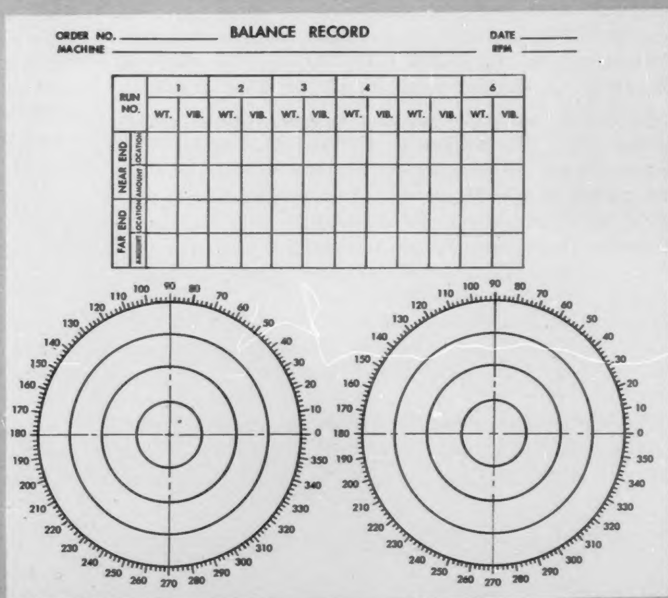
VECTOR DIAGRAMS with weight and vibration measurements plotted. **(FIGURE 2)**



VECTOR DIAGRAMS of weight and vibration measurements for combined static and dynamic balancing tests. Final tests for zero unbalance and zero vibration are not shown. **(FIGURE 3)**



PHASE ANGLE lags behind rotor heavy side with the amount depending on speed of rotor to be balanced. **(FIGURE 4)**



BALANCE RECORD SHEETS provide convenient means of recording and calculating data from balancing tests. **(FIGURE 5)**

tions the vibration will not be the same at both bearings and trial runs will be necessary to determine the nature of the unbalance. The corrective weight can be located at the ends, at the center, or distributed along the length of the rotor but must be distributed symmetrically with respect to the center of gravity of the rotor or a dynamic couple will be introduced.

Similarly, dynamic unbalance, Figure 1c, will under uniform conditions cause vibration equal in amplitude but 180° apart in phase angle at the two bearings. The corrective weights must be so located as to produce a couple about the center of gravity of the rotor.

The usual condition of unbalance is represented by Figure 1d. Both ends of the rotor should be balanced simultaneously since balancing one end at a time is at best a very lengthy procedure. To use an involved mathematical procedure for the determination of balance correction based on data obtained by trial runs may lead to incorrect results owning to non linearity of response to balance weights and inaccuracies in the data. A simple and effective method is to treat the unbalance as a combination of static and dynamic unbalance by progressively correcting one of these components at a time.

It is helpful to prepare balance record forms similar to Figure 5 for tabulating and plotting the balance data.

An example, Figure 3, will serve to explain the procedure. In Figure 3 the diagrams under I represent the data for end I of the rotor and those under II represent the data for end II. The initial vibration reading at end I is .0031 inch at 110 degrees and at end II is .0043 inch at 40 degrees. These are drawn as 0-1 in Figure 3a. As a rule if directions of the initial vibration vectors differ by less than 90 degrees a static correction weight is applied first. A trial weight of 10 oz. is added at each end of the rotor at 180 degrees. The trial static weights are represented by the vectors O-A, Figure 3b. The vibration measurements obtained on the static weight trial run are .007 inch at 165 degrees at end I and .0052 inch at 115 degrees at end II, 0-2, Figure 3a. Now the effect of static weight on the vibration at each bearing is determined by drawing lines 1-2. It is desired to apply a static weight correction which will nullify the static unbalance and leave only a dynamic unbalance. From a study of the diagram it can be deduced that by reducing the length of vectors 1-2 by one-half and rotating them 75 degrees counterclockwise the desired effect will be accomplished as shown by the broken line 1-3. Accordingly the static weight is reduced to 5 oz. and shifted to 255 degrees. The results of this check run with this weight are plotted as 0-4, Figure 3c.

A run is then made with trial dynamic balance weights in the rotor. The weights are represented by vectors 0-C, Figure 3d, and the measurements obtained from the trial run are plotted as 0-5, Figure 3c. From examination of diagram 3C, it is apparent that the weights should be shifted clockwise 30 degrees. The dynamic balance weights are relocated as shown by O-D. If a check run shows that further balance correction is required the correction is based on the data from the previous trial runs. The correction weights for static and dynamic unbalance may be combined vectorially into a single weight for each end of the rotor.

Flexible rotor represented by three discs

An additional factor is involved in the determination of static weight correction of flexible rotors. A flexible rotor is one whose normal operating speed is above its critical speed; such a rotor usually has a length of three or more times the diameter. The term "static balance" is a misnomer in this case for a rotational test at two speeds is necessary to find the correct distribution of "static" weight.

Assume a rotor as shown schematically in Figure 1e to be balanced at a selected speed by the addition of weights to the end discs only. The unbalance at the center disc causes a deflection of the shaft which adds to the unbalance and which varies as a function of the speed. At the selected balancing speed correction has been made for the unbalance caused by the shaft deflection at that speed. However, at lower speeds, since the deflection caused by the center unbalance will be less, the static weight which was added to the end discs will be excessive. At higher speeds more weight would be necessary in the end discs. A rotor of this type, if balanced at only two axial locations, can be balanced for only one speed.

The procedure for balancing this type rotor is to first balance at the critical speed by adding weights to the ends of the rotor. Then the rotor is balanced at operating speed by the method previously described but with the "static" weight added at the center of the rotor. Following the balancing at operating speed it may be necessary to re-balance at the critical speed. Frequently, the weight at the center is located diametrically opposite from the weights at the ends.

In the case of a generator with an overhung exciter the balance may be excellent insofar as vibration at the bearings is concerned, but the exciter commutator may be rough because of a bow in the rotor shaft caused by incorrect distribution of balance weight. To improve the commutator by adding weight to the exciter will probably increase the vibration at the bearings. The solution is to re-distribute the static weight on the rotor, that is, to add weight at the center as well as at the ends of the rotor. A rough rule is that weight at the center of the rotor is about twice as effective as weight at the ends.

Conditions necessary for balancing

For accuracy of results, successive balance runs should be made under identical conditions of speed, temperature, load, etc. A change in speed will change the phase angle as well as the amplitude of vibration. The phase angle or "high side" lags behind the heavy side of the rotor as shown in Figure 4. At low speed the lag angle is very small. In the region of the critical speed the lag angle changes rapidly, passing through 90 degrees at the critical speed. Above the critical speed the lag angle approaches 180 degrees.

Temperature, load and field current may affect the balance of a rotor. It is therefore desirable that these factors be held constant at normal operating conditions when the vibration is measured. Each run should be of long enough duration to permit the vibration to reach a steady condition. When vibration is erratic or does not respond to balancing, causes of vibration other than unbalance should be investigated. Such causes of vibration are coupling misalignment, a bent shaft, a surface defect on a journal, a journal out of round, a stationary part rubbing on the shaft, loose bearing parts or loose members on the rotor.

A few basic rules for balancing, therefore, plus simple equipment, enables most problems of unbalance to be solved in a relatively easy way without the use of balancing machines.

Building Blocks of Marine Power

★ ★ ★

H. OMAN
Motor-Generator Section
Allis-Chalmers Mfg. Co.

Standard diesel-electric marine generator and motor combinations have opened a new era of freedom in the design of ships up to 12,000 shaft horsepower.

UP to the present day marine designers have always looked upon each vessel as a separate design problem, seldom using the same propulsion drive for two boats unless they were sister ships or part of a fleet. Not until the diesel electric drive reached its present state of efficient performance did standardization of unit size drives become both practical and desirable.

The electric drive entered the ship propulsion field almost as soon as the internal combustion engine was invented. After an unsuccessful steam submarine was built in 1895, the submarine propulsion problem was solved in 1902 in a manner which was not changed, basically, for 40 years. In this service a propulsion generator is driven by an internal combustion engine, and the output from this machine is utilized for surface propulsion and for charging batteries. The propulsion motor is driven from storage batteries when the vessel is submerged.

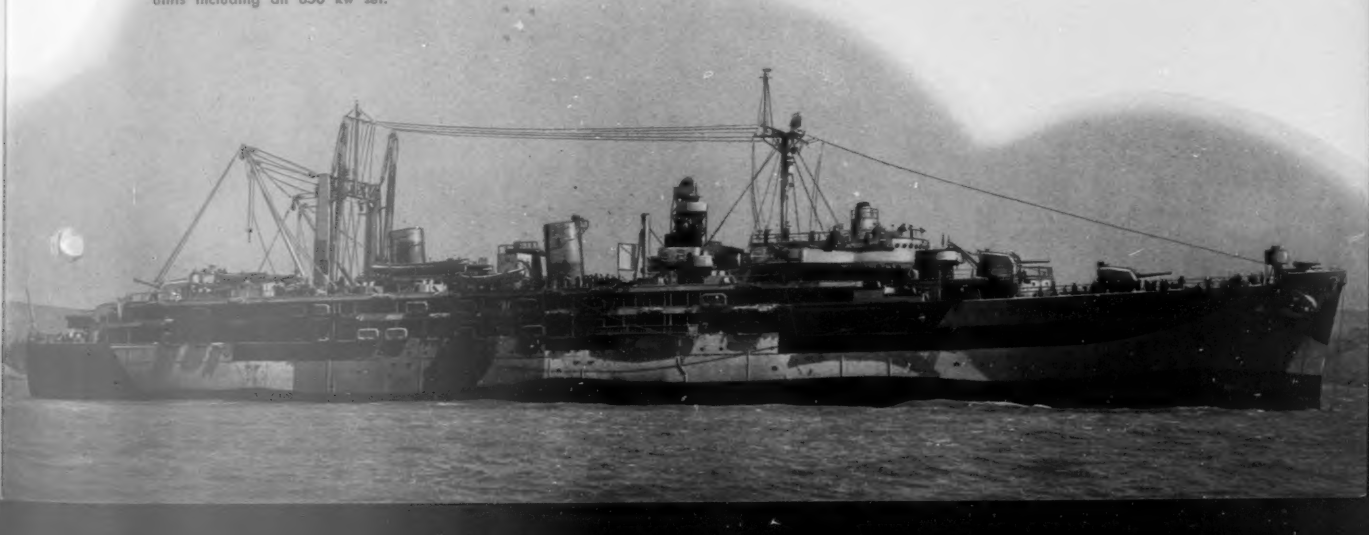
Ship builders and operators were interested in the diesel engine right from its start. The first marine diesel engine was built in 1902, and it was followed in 1905 by a reversible engine. In 1910, a single 370 hp diesel engine was installed on a small ship called VULCANUS. In 1913, the first American diesel engine was built by the Winton Company.

The reason diesel engines interested ship owners becomes apparent from Figure 1. Although the saving in oil consumption may not necessarily mean a saving in actual fuel cost (in some parts of the world diesel oil costs as much as 27 percent more than bunker oil for boilers), less weight in fuel oil means that the vessel has more capacity for cargo; or with the same cargo, a greater cruising range.

Within a relatively short time, the diesel engine gained wide acceptance in the marine field. Lloyds Register of Shipping shows that from 1928 to 1938, the diesel powered tonnage increased from 5,432,302 to 15,232,953 tons.

Diesel electric drive gives low speed advantages

Early in the diesel engine development, marine architects suspected that some advantage might be gained by utilizing an electric coupling between the diesel engine and propeller. One of the main disadvantages of direct diesel drive for marine propulsion is that the diesel engine cannot produce more than full speed propeller torque at reduced speeds. This condition is illustrated in Figure 2. It is noted that



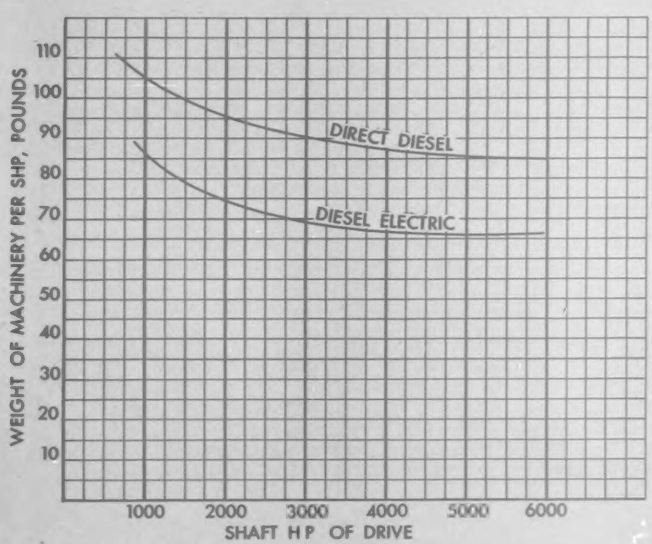
SUBMARINE TENDER, the U. S. S. Howard W. Gilmore, is equipped with 11,520 shp diesel-electric drive and control, and auxiliary m-g units including an 850 kw set.

Type of Prime Mover	Overall Efficiency (from fuel input to power output)
Steam engine	6-9 percent
Steam turbine	16-30 percent
Gasoline engine	22-28 percent
Diesel engine	32-38 percent

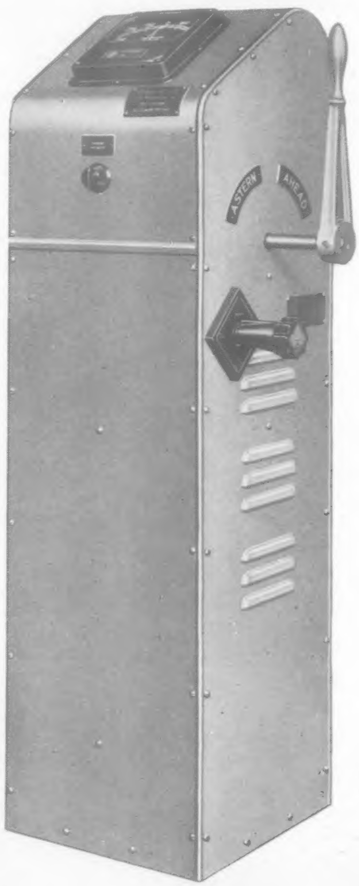
RELATIVE FUEL EFFICIENCIES of prime movers. **(FIG. 1)**

Type of Load	Diesel Direct Drive			Diesel Electric Drive		
	Propeller RPM Percent	Propeller Torque Percent	Available "Drawbar" HP. %	Propeller RPM Percent	Propeller Torque Percent	Available "Drawbar" HP. %
Boat running free	100	100	100	100	100	100
Light tow	90	100	90	95	105	100
Medium tow	85	100	85	90	113	100
Heavy tow	80	100	80	85	117	100
Pulling or pushing at standstill ..	70	100	70	77	130	100

CHART OF TYPICAL INSTALLATIONS shows hp and torque output of direct-connected diesel and diesel-electric d-c drives. **(FIG. 2)**



THESE CURVES compare weights of direct diesel and diesel electric drives. **(FIG. 3)**



CONTROL LEVER of pilot house control stand selects propeller speed which is read in shaft rpm. Lever at bottom switches control to other station. **(FIGURE 4)**

with heavy tows and pushing or pulling on very slow moving objects, the vessel loses as much as 30 percent of its engine horsepower. This need not be the case in a diesel electric drive where the electrical machinery can be designed to give higher torques at low-speed — thus essentially full engine power can be transmitted to the propeller at most speeds and tows.

First successful commercial application of the drive was on a fishing trawler named the *Mariner* in 1919, followed in 1922 by use on the *Golden Gate*, a ferry boat.

High speed diesel reduces weight

The development of the high speed diesel engine focused more attention on the use of diesel electric drives. Engine weight per horsepower was cut in half and volume per horsepower was reduced to one-third in many ratings. For the first time, the weight of all the diesel electric equipment on the drive was reduced below the weight of an equivalent direct drive diesel engine. (Figure 3.)

As a result of this accelerated interest, an effective and dependable remote control was developed. With this control, the diesel engine can run between 50 percent and 100 percent of rated speed, while vessel speeds from zero to full in either direction can be easily selected with a control lever in the pilot house (Figure 4). As the speed control lever is moved from zero to full ahead, the generator fields are first brought up to full strength, and then the engines are accelerated to full speed by means of torque motors on the governor. (Figure 5.)

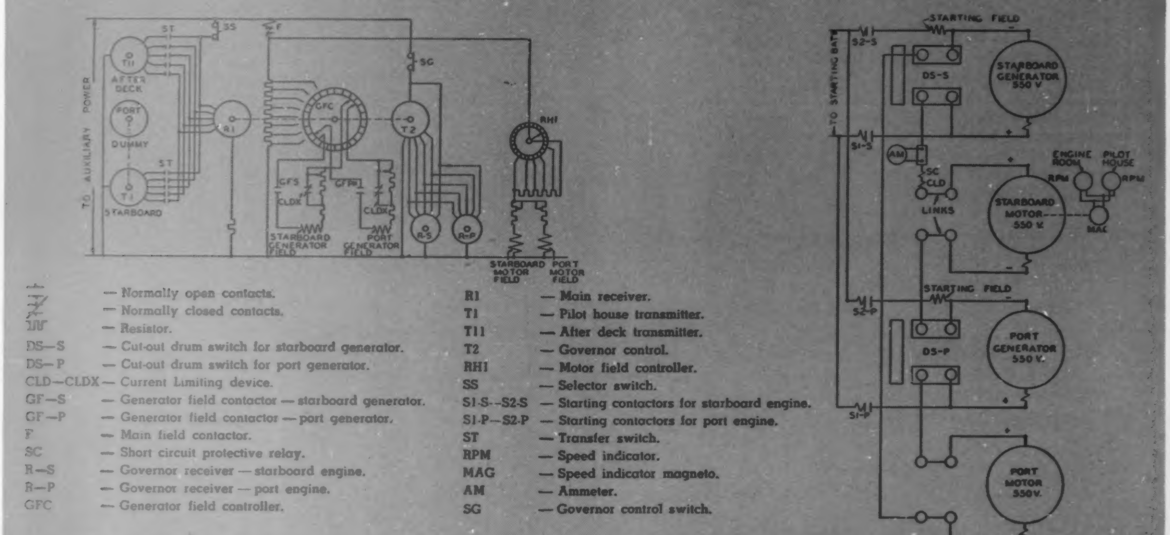
Diesel electric drives were in use on hundreds of ships at the beginning of World War II. Ferry boat and tugboat owners found them useful in ships operating in crowded metropolitan waters, because the vessel speed and direction could be regulated from the pilot house without the necessity of signalling the engine room. Furthermore, the engineer was not required to respond to frequent calls.

War shortages increased applications

Wartime turbine and double-reduction gear shortages caused diesel electric drives to be even more widely applied. All available gear and turbine capacity had to be used for production of machinery for destroyers, cruisers, battleships, and aircraft carriers. When it became suddenly necessary to build hundreds of escort vessels to guard Atlantic convoys against submarines, it was decided to utilize the nation's experience in building diesel electric drives. During this war program, certain engine and generator combinations became more popular than others, and these combinations were utilized in various multiples to give shaft horsepowers up to 12,000.

It was soon evident that certain advantages could be gained by utilizing high-speed single reduction geared motors to drive the propeller shaft, rather than low-speed direct-connected motors. In most cases, the motors and gears actually weighed less and cost less than an equivalent low speed motor coupled direct to the shaft.

Further studies indicated that, from an overall standpoint, the most economical propulsion arrangement could usually be obtained by having the same number of propulsion motors as propulsion generators.



BASIC CONTROL diagram illustrates direct-current diesel electric drive with two 605 kilowatt propulsion generators and two 765 horsepower propulsion motors. **(FIGURE 5)**

Unit type drives are built

From this war experience and research, the unit type diesel electric type has evolved. With this unit type of design, any desired vessel shp from 500 to 12,000 can be obtained from different combinations of six generator (and engine) and six motor ratings. Figure 6 represents a typical manufacturer's ratings for direct current. For many large ship applications, alternating-current propulsion drives are more economical than direct-current drives, particularly where frequent, precise low-speed maneuvering is not necessary. A series of standardized a-c drives have been designed around a propulsion unit consisting of one diesel engine, one 1160 kw, 750 rpm, 2300 volt generator; and one 1510 hp, 750 rpm synchronous motor.

Diesel-Electric, Direct-Current Marine Propulsion Drives Standard Units

Vessel SHP	Number of Engines	Generator Rating, kw	Number of Motors	Motor Rating, hp
500	1	410*	1	510
650	1	530*	1	665
750	1	605*	1	765
1000	2	410*	2	510
1000	1	814*	1	1020
1300	2	530*	2	665
1350	1	1110	1	1380
1500	2	605*	2	765
1600	2	650*	2	815
2000	2	814*	2	1020
2700	2	1110	2	1380
3000	4	605	4	765
3000	3	814	3	1020
4000	4	814	4	1020
4050	3	1110	3	1380
5400	4	1110	4	1380
6000	6	814	6	1020
8100	6	1110	6	1380
10800	8	1110	8	1380

NOTE: All generators operate at 750 rpm when full power is required. Full-power speed of motors is 700 to 875 rpm, depending on wind, trim, and tow. All drives with an even number of engines are adaptable to twin-screw vessels. Maximum voltage in propulsion loop is 560.

SHP=(Total Motor HP) x (Approx. 98% gear efficiency).

*Integral auxiliary generator available for auxiliary power.

TYPICAL STANDARD UNIT TYPE diesel-electric drives. **(FIGURE 6)**

The advantages of the unit type drive to the marine architect are many. His designs can determine what vessel shp is required. From the use to which the vessel is to be put can be determined how many engines will be required to get the desired insurance against complete loss of propulsion. Generating units can be placed in the ship wherever good balance and efficient space utilization permit and propulsion motors can be installed in the stern to eliminate the necessity of a long propeller shaft.

Design of the propulsion control for the d-c drive has also been adapted to standardized propulsion motor and generator combinations. The generator transfer switch itself (which permits removing the engine-generator set from the propulsion circuit without stopping the remaining engines) along with the engine starting contactor, overload relays, and other miscellaneous control items are mounted in the transfer switch cabinet which, in turn, is mounted on the generator. Only field and control leads need be wired to the propulsion control panel. (Figures 7 and 9.)

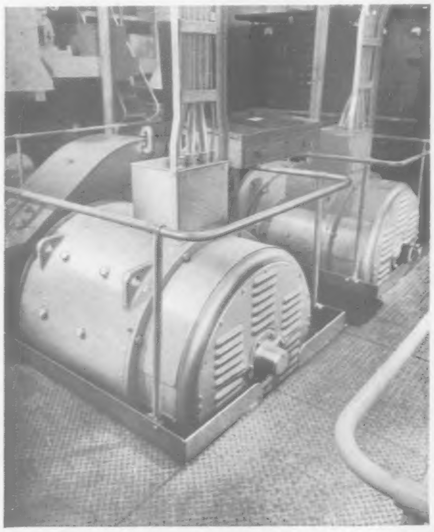
Features specified for standard units

Certain features in the design of the standardized propulsion motor and generator units were frequently specified by marine architects. For example, one standard requirement was for all controls to be placed on the inboard side of the engine and generator, since the outboard side might be quite close to the hull, interfering with operation of controls on the cutout switch cabinet.

Because spares have to be furnished for generators that are not alike, it is not desirable to have two separate generator designs on a given ship to make possible port-starboard construction. The problem was finally solved by mounting

PROPELLER SPEED can be controlled by left handwheel on propulsion control panel in main engine room of 1500 shp tugboat. Speed may also be controlled from pilot house control stand, as shown in Figure 4 on page 30. **(FIG. 7)**

TRANSFER SWITCH CABINET can project to either side of generator, making identical port and starboard generators possible. This construction reduces requirements for generator spare parts. **(FIGURE 8)**



HEAVY CABLES carrying current come directly from the generators to these two 765 hp propulsion motors with reduction gear. For a 3000 shp single screw drive two more motors could be mounted on other side of a similar gear, coupled to same pinions. **(FIG. 9)**

the transfer switch cabinet on top of the generator, as mentioned above, and extending it toward the operating position. Thus, the adaptability of a generator to a port or starboard location is determined only by whether a port or starboard transfer switch cabinet is mounted on it.

Another feature specified by architects designing small vessels is ship's service power from main propulsion engines. As a result, those ratings of the standardized generators which are designed primarily for small vessels are equipped with integral auxiliary generators. The integral construction was selected in preference to an overhung construction to permit ready maintenance of the bearing that supports the front end of the generator. This integral auxiliary generator is rated at full capacity for all operating speeds of the engine, and constant voltage output is maintained with a regulator. When the vessel is at sea and auxiliary power requirements are small, it is possible to shut down auxiliary engines and obtain auxiliary power at the main engine fuel rate.

Power is provided for extra equipment

The diesel electric drive has a unique advantage in that simple alterations in the control circuit will enable standard propulsion generators to perform unusual service.

On a tuna boat, for example, which carries extremely valuable refrigerated cargo, the refrigeration load is normally carried by auxiliary engine-driven generators. However, because of the high value of tuna fish, it is desirable to have additional insurance against refrigeration power failure. This can be readily provided in a diesel electric drive where auxiliary power can be obtained from one or more of the propulsion generators by a simple control feature.

Although its higher original cost may be a drawback, if the use of the diesel electric unit type drive can develop as fast as its technical construction, it will remain an important factor in future marine propulsion and standardization of unit size drives will be greatly advanced.

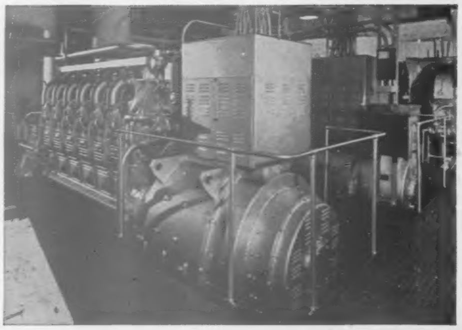
Diesel-Electric Drive Powers First Lakes Carrier

Conversion from 38 years of steam propulsion to diesel-electric drive gives the ore carrier E. J. Block (left) the distinction of being first of the Great Lakes ore carriers to turn to this new type of power plant.

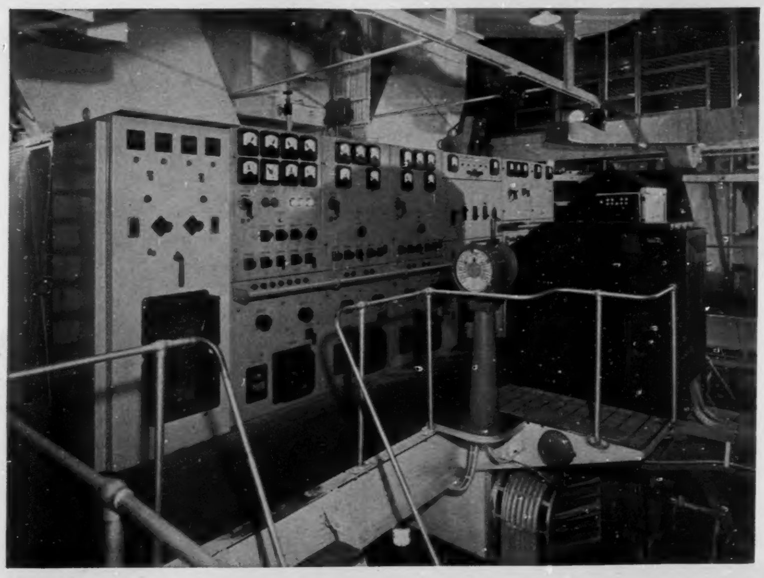
All main propulsion electrical equipment is Allis-Chalmers, together with a new mechanical remote positioning and indicating system which permits direct control of the engines from the bridge. Other improvements new to lake shipping include electrically driven windlasses, radar, and automatic steering.

That the new propulsion has definite merit was established in the Block's trial runs in September. While proceeding at full speed of 13 miles an hour, she was thrown into full speed astern and stopped in 1,560 feet within 3 minutes and 19 seconds.

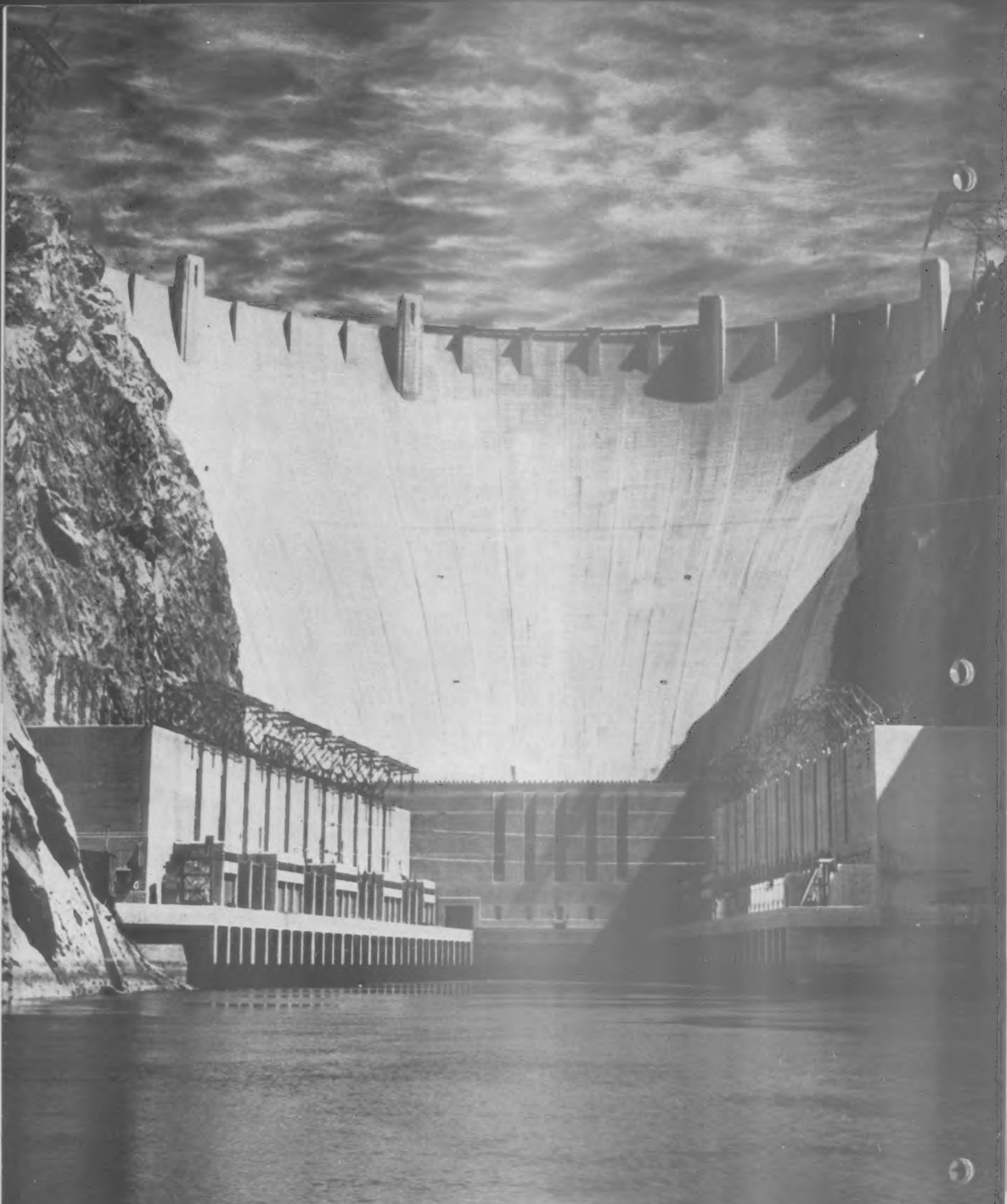
An increase of approximately seven percent in speed and cargo space are expected to result from conversion of the Block.



THE BLOCK'S new power plant has two 1,200 hp diesel engines that drive generators supplying electric power to two main propulsion motors which, in turn, are geared to the propeller shaft. The Block's speed has been increased about one mile an hour.



CONTROL DESK for main propulsion motors and generators and auxiliary control board are above engine room. Although pilot house control stand normally controls vessel speed in fine adjustment, an engine order telegraph is also installed.



PRODUCTION OF POWER at Boulder Dam is hailed with a tenth anniversary ceremony this year. Seven states benefit from this and smaller dams which control run-off water of the Colorado and its tributaries. Important to Boulder's efficient functioning are 12 huge vertical cast steel spiral casing turbines — seven of them built by Allis-Chalmers. A major by-product of the dam system has been expansion of recreational opportunities.

Fused Starters Protect High Voltage Equipment

W. J. HERZIGER
Electrical Control Section
Allis-Chalmers Mfg. Co.

New standard industrial control equipment offers simple starting and surge protection for large motors.

FOR almost half a century circuit breakers have been the only means of providing high interrupting capacity control on large high voltage systems. Now, however, short circuit protection from 150,000 to 250,000 kva can be obtained economically and efficiently on 2200 to 4600 volt systems by the use of standard industrial control equipment. A brief analysis of the requirements for good short circuit protection will prove the merits of this type of motor control.

The magnitude of short circuit current which flows toward and into a fault on any power distribution system depends upon the fault resistance and the system arrangement and capacity. Whether or not the resulting disturbance to the power system is severe enough to result in complete plant shut-down depends upon the characteristics and speed of the protective devices used.

The initial system fault current assumes a transient characteristic which reaches its maximum within the first cycle and then decreases on a transient curve. In Figure 1 it can be seen that successive peaks become lower and lower until a steady value of short-circuit current is reached.

The total wave of transient short-circuit current whose crests fall along curves CD and EF is composed of an alternating and a direct current component. The transient characteristics of the connected synchronous machines result in a transient symmetrical a-c component of current on which a transient d-c component may or may not be superimposed. The value of the d-c transient component depends upon the point on the voltage wave at which the short circuit occurs and may result in a wholly asymmetrical wave about the zero line.

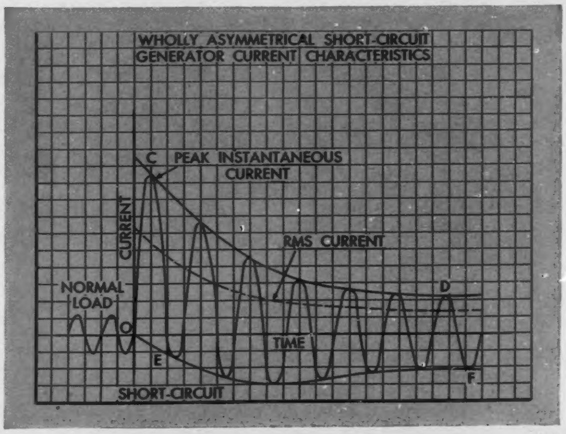
Under this condition the rms (root mean square) current is approximately 1.73 times the rms value of the a-c component alone. This factor must be considered in determining the interrupting rating required of any protective device capable of operating in the first cycle of short circuit current.

The prime requisite, therefore, in the design of large a-c power systems is the correct proportioning of the components used, in accordance with the magnitude of the greatest short-circuit current which may result from a breakdown of insulation.

Motor control requirements

In preparing a new plant layout or modifying an existing installation, the industrial engineer must look at the problem from both an economical and a workable point of view. In deciding the most satisfactory type of motor control he would demand the following characteristics:

1. The individual motor controller should have adequate interrupting capacity to meet any requirement of the power system involved.
2. It would be desirable for the motor controller to have the ability to limit the magnitude of the short-circuit current well below that which the system is capable of producing.



WHOLLY ASYMMETRICAL short-circuit generator current characteristics show peaks become lower until steady current value is reached. (FIG. 1)

3. The controller should be capable of interrupting maximum short-circuit currents without generating gas or flame.
4. It should combine the advantages of high-interrupting capacity ability with accurate motor overload protection and low maintenance characteristics.
5. It should be reasonably silent in operation to prevent unnecessary discomfort to operating personnel but should also provide suitable means of detecting a short-circuit interruption.
6. It should be an individually complete unit totally metal-enclosed to afford maximum protection to personnel and result in an economical attractive installation.
7. It should have low initial cost.

Fused controller meets requirements

These requirements for a satisfactory 2200 to 4600 volt industrial type motor control have been met and a number of unique advantages added through the development of a properly coordinated current-limiting fused controller, shown in Figure 2.

Successfully used in rubber and paper mills, cement plants, oil refineries, power plants, pumping stations, and general industrial plants, a typical unit of this new type controller is comprised of these major parts:

(1) High interrupting capacity current-limiting fuses.

(2) Accurately calibrated thermal overload relays.

(3) Low maintenance-long life primary contactor.

A fundamental controller scheme employing these features is shown in Figure 3.

The high interrupting capacity current-limiting fuses used are of the disconnect type. The fuses serve a dual purpose of interrupting media and disconnecting switch. A hook-stick can be used to disconnect the fuse, completely isolating the controller for greater safety to maintenance personnel.

The fuse unit is specifically designed for short-circuit interruption service on individual motor circuits and is never applied for normal overload protection. It should be emphasized that successful operation of the complete controller depends upon exact coordination between fuses and thermal overload relay and at no time should any attempt be made to apply the fuse on existing control installations.

The current-limiting fuse consists of multi-section wires embedded in a granular quartz filler enclosed in a heat-resistant glass tube. The ends of the conducting wires are connected to metal spiders which are in turn welded to the terminals or ferrules of the fuse unit.

On short circuits the conducting elements melt before the current in the first major half cycle loop can reach its peak value. The total energy involved in clearing a short-circuit is exceptionally low because the fuse operates with such great speed.

Operation of the fuse is explained in Figure 4, which shows an actual test oscillogram.

FUSED MOTOR CONTROL consists of incoming line panel, exciter control panel and two 700 hp, 2300 volt reduced voltage synchronous motor controllers. (FIG. 2)

Assume that at point A a short circuit is applied to the system which causes the current I to lag voltage E by 90°. The dotted current curve shown indicates the available short-circuit current which would flow under identical switching conditions if current-limiting fuses were not applied.

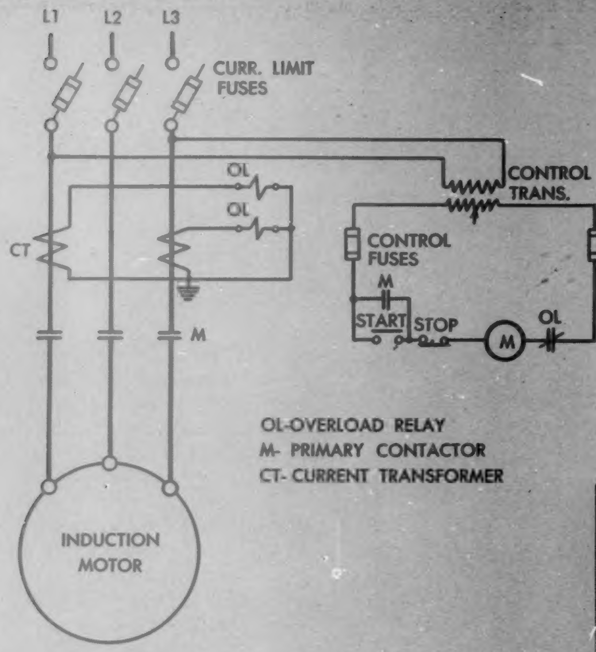
The solid current curve I' indicates the current-limiting characteristics and high interrupting speed of the fuse. The solid shaded area represents the melting time of the conducting elements, that is, the melting time of the first section of conducting element. The dotted area represents the arcing time beginning from the first instant that the conducting element begins to melt.

By making the conducting elements of multi-sectioned wires, the advantage of introducing a progressive amount of current-limiting effect is afforded. It is the ability of introducing a progressive current limiting effect which aids system stability and limits the recovery voltage to safe values which are within recommended high potential test values. Existing system insulation is thus safeguarded against breakdown resulting from excessive recovery voltage.

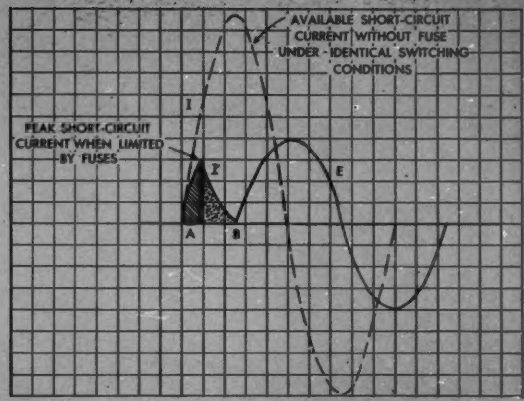
Figure 5 shows a typical fuse unit of which a portion of quartz filler has been removed to show the fulgurites formed after interruption of 40,000 amps rms at 2300 volts. The fuse, being completely enclosed, does not give any audible indication of interruptions, but a target indicator gives an external indication when the fuse is blown.

Overload relays give accurate coordination

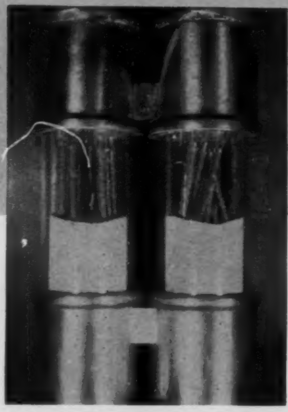
Accurate coordination of fuses and contactor is provided by compensated thermal overload relays of the type shown in Figure 6. A compensating element recalibrates the tripping



FUNDAMENTAL CONTROLLER scheme of typical fused full voltage motor starter employs three major parts — current-limiting fuses, thermal overload relays and primary contactors as illustrated above. **(FIG. 3)**



HIGH INTERRUPTING speed of the current-limiting fused controller is illustrated in actual test oscillogram. **(FIG. 4)**



FULGURITES formed after interruption of 40,000 amps rms at 2300 volts in typical fuse unit with part of quartz filler removed. **(FIG. 5)**

SPIRAL HEATER completely surrounds a spiral bi-metallic element in compensated overload relays to obtain efficient thermo-dynamic characteristics. **(FIGURE 6)**

mechanism so that the heater element is not affected by variations in ambient temperatures. Automatic recalibration prevents unnecessary motor stoppage and allows the use of maximum motor capacity.

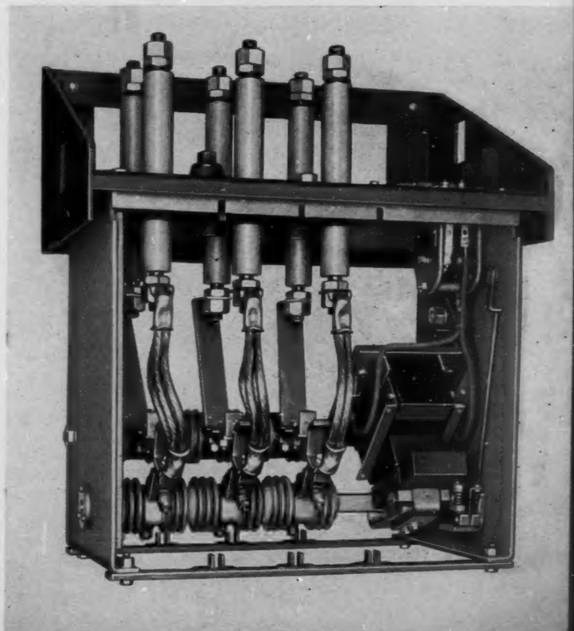
Flexibility of adjustments for varying load requirements is obtained through a plus or minus 20 percent trip adjustment.

On a properly coordinated controller the overload relay characteristic curve will be such that under locked rotor conditions the primary switch will always be opened before the fuse elements melt.

There are in use, at the present time, two types of primary switches, the high voltage oil-immersed contactor and the high voltage air break contactor. Each is readily adaptable for this type of service and should be selected to suit the particular application involved.

The oil-immersed contactors (Figure 7) are designed for heavy duty industrial motor starting service. The primary advantage of contactors is the elimination of all latching equipment and mechanical levers subject to wear under frequent starting service. Moving parts have low inertia so that damage due to repeated shock is eliminated. All parts are designed strong enough to withstand any values of fault current which the fuse will allow to pass.

It should be noted (Figure 3) that on a properly coordinated fused motor control it is not necessary to latch in the primary switch or energize the closing coil (M) from a separate d-c source. When the line voltage drops at the instant of short circuit, the controller fuses will clear the fault before the contactor contacts can part to interrupt any fault current. This is true whether the contactor is required to



OIL-IMMERSED CONTACTORS built for heavy motor starting duty have no latching equipment or mechanical levers. **(FIG. 7)**

close on a short circuit or whether the fault develops during normal motor operation.

For applications where the duty cycle is rapid, causing frequent maintenance of conventional control equipment, high voltage air-break contactors should be used.

These air-break contactors are designed with highly efficient blow-out coils which rapidly carry the arc away from the contact tips into specially designed arc chutes, where the arc is quickly cooled and extinguished. Operating experience with these contactors in service where frequent operations are required with only routine inspection and maintenance has been completely satisfactory.

Applied to all alternating-current motor drives

High interrupting capacity industrial motor controllers of this current-limiting fused type have been successfully applied on all types of a-c drives. The controllers are designed to be of either the full voltage or reduced voltage starting type using starting auto-transformers or reactors.

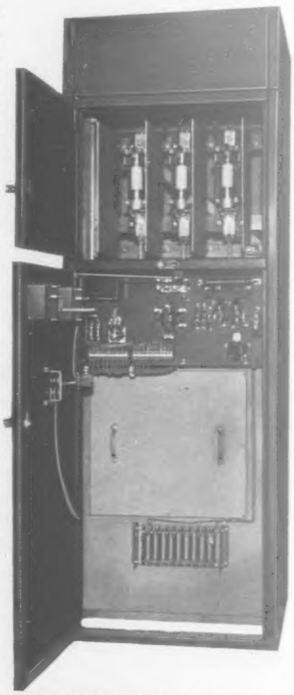
Squirrel cage induction motor controllers of this type are especially recommended for use with motors driving pumps, blowers, conveyors, compressors, generators, fans and other general purpose industrial applications where heavy duty and reliable starting equipment providing sufficient interrupting capacity is required.

Completely automatic synchronous motor controllers utilizing the same basic layout of fuses, relays and contactors are able to provide positive synchronizing of driving motors under the most difficult starting conditions. Positive synchronizing is accomplished by means of a polarized field frequency relay which accurately responds to apply the field excitation at the most favorable pole position.

A typical synchronous motor controller of the reduced voltage starting type is shown in Figure 8.

Extensive laboratory tests have proved the ability of these controllers to successfully close on a system short circuit capable of developing a maximum of 150,000 kva at 2300 volts.

The development of satisfactory fused controllers now offers a broad field for application on industrial systems where high interrupting capacity protection is required and which previously dictated the use of large circuit breakers. There are strong indications that future design specifications will make generous use of this improved type of industrial motor control.



SYNCHRONOUS motor starters use same system of fuses, relays and contactors to give positive synchronizing of driving motors. (FIGURE 8)

New Products

New Idea Operates Liquid Slip Rheostat

Applicable to most wound rotor motors, a new liquid slip rheostat uses a principle which is a combination of variable electrolyte level and movable electrodes. One electrode is always covered by the electrolyte to prevent the flashovers caused by conducting vapors inherent in older designs. This rheostat gives a wide range of speed control with step-less regulation, greater momentary overload capacity, and has smaller overall dimensions.

Motor Control Simplified by Relay

Included on all synchronous motor starters to simplify the control is a new type polarized field frequency relay. Since the relay is responsive to the induced field current of the motor during synchronizing, it applies excitation at the maximum motor speed and at the most favorable pole position. The motor then exerts its maximum torque to pull the load into synchronism in minimum time, with least shock to the driven machine and power system. Automatic field removal on pull-out and re-synchronizing are inherent in the design.

Fused Starters Ensure High Voltage Protection

Complete protection for motors, equipment, and operating personnel is afforded through a new type H line of motor starters. Disconnecting-type power fuses provide built-in short circuit protection up to 150,000 kva at 2300 volts and 250,000 kva at 4160 or 4600 volts. The fuses, which are coordinated by an accurate overload relay to work with a high-voltage oil-immersed contactor, cut off short circuit current in less than one-half cycle to safeguard both starter and motor. Complete details in Bulletin 14B6410.

Substation Is Compact, Portable

A unique trailer type unit substation built to size and weight limitations provides a wide range of primary and secondary voltages which are quickly varied by external operating handles. This permits the unit to be employed in many places on a system as a spare and substitute transformer. Circuit breakers with protective relays and metering equipment are mounted on the low voltage side so all functions of a complete substation are filled.

MORE FACTS about these new products are available on request. Write the Allis-Chalmers ELECTRICAL REVIEW, Allis-Chalmers, Milwaukee 1, Wisconsin.

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